ELECTRICAL DISTRIBUTION ENGINEERING

BY

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PREFACE

Although the electrical distribution system has always been an essential part of any project for the generation and sale of electrical energy, its design was formerly considered as more of an art than a science. It is only in comparatively recent years that the necessity for careful technical engineering on the distribution system has been generally recognized. With the increasing size and complexity of these systems, the field of the distribution engineer is continually widening and his position in the power company's organization becoming more important.

Distribution engineering requires a knowledge of the fundamentals not only of electrical engineering but also, to some extent, of civil engineering and of engineering economics. The author has attempted to bring together in this book the essentials of these three branches of engineering as they enter into the design of distribution systems and to point out the methods of their application. Rather than to give a recital of past or present practice, it has been the intention to show as far as possible the reasons why certain things are done and to indicate methods whereby the student may determine the solutions of his own problems. The science of electrical distribution is developing very rapidly as to practice, but the basic fundamentals are well established.

The material here given has been collected during the author's thirteen years' experience in distribution engineering work with The Detroit Edison Company. Naturally many of the practices of that company are included for purposes of illustration. Acknowledgment is also made to the publications of the Overhead Systems Committee, N.E.L.A., from which has been borrowed a considerable amount of material, especially tables and illustrations of generally accepted standards.

This book is offered with the hope that it will prove of value not only to the student, as a text, but also to the experienced engineer, as a ready reference.

HOWARD P. SEELYE.

DETROIT, MICH.
February, 1930.

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CHAPTER I

THE DISTRIBUTION SYSTEM

One of the most important parts of the property of any company whose function is the generation and sale of electrical energy to a diverse group of customers, is its *distribution system.* In the usual case, every kilowatt-hour sold must pass through some form of a distribution system, more or less complex as the case may be, on its way from the generator to the customer. That system may vary from a simple single circuit, serving one or more customers, to a far-spread network of conductors through which the energy generated flows, being subdivided and resubdivided until it finally reaches a vast number of relatively small users. It has even been said that, on the average, 80 per cent of the cost of serving a customer with electrical energy lies in the cost of distribution. While such a large percentage may not hold true in many cases, it still may be emphasized that usually the cost of distribution is a major part of the cost of delivered energy and likewise the investment represented in the distribution system is a major part of the investment in the whole property.

Strictly speaking, the distribution system might comprise the whole system by which the energy is distributed from the generators to the customers. This would include transmission lines and substations as well as the local distribution system which radiates from the points of concentration (substations) to the users. Transmission design and substation design, however, are, for the most part, of considerably different character than the design of the local distribution, and their features have been well covered elsewhere. It is the province of this book to deal particularly with engineering design as applied to this local distribution and where the *distribution system* is hereafter

mentioned, it will be understood to so apply and not to include transmission or substations unless they are specifically mentioned. Of course, it is sometimes rather difficult to draw an exact line between transmission and distribution but, in general, it is assumed that transmission refers particularly to the handling of wholesale quantities of energy between the point of generation and other central points from whence the distribution system carries it to the consumers. It must be recognized, however, that on any system, best engineering results are not obtained unless the design of the various parts is coordinated, that is, the distribution system cannot be effectively planned without regard to the plans for the transmission and substation elements.

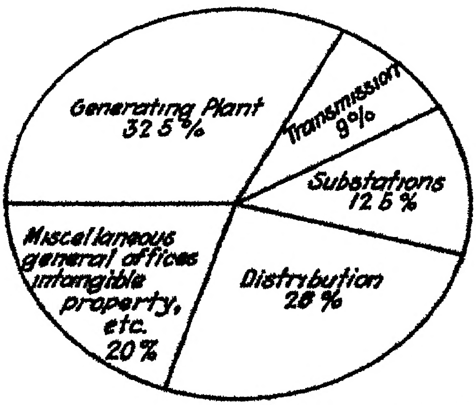

Fig. 1.—Division of total investment in system for generation and distribution of electrical energy.

The relative importance of the distribution system can perhaps be best exemplified by the proportion of the total investment in the system property which it represents. This will, of course, vary somewhat with the nature of the company and the type of loads served. Figure 1 shows a diagram of the division of the total investment among various classes of property for a typical case of a company serving a diversified load of power, light, street railway, etc. It is probable that the figures for other companies of a similar character will not be widely different. It will be seen that the investment necessary for the distribution of the energy generated (including transmission and substations) is nearly 50 per cent of the total investment of the company and 50 per cent greater than that in generating plants. Of this amount, over one-half is in the distribution system, *i.e.*, primaries, secondaries, transformers, etc. and this alone is nearly as great as the investment in generating plants. As a concrete example, if a system had a total property value of $25,000,000, on the basis of the division shown in the diagram, the generating plants would represent about $8,100,000, the whole system for distribution about $12,000,000. Of this, transmission would

represent $2,300,000, substations $3,200,000, and local distribution system $6,500,000

Figures published from time to time on the total value of additions being made to generating and transmission and distribution systems in the United States usually show fully as much expenditure in the latter two as in the first. For example, for a period of 5 years from 1924 to 1928[1] the total cost of these additions and extensions is divided as follows.

	Percentage
Generating plants	44 7
Transmission (including substations)	24 5
Distribution	30 8
Transmission and distribution	55 3

A considerable portion of the cost of delivering energy to the customers is incurred in the proportion of the energy generated which is lost in its distribution. This proportion will, of course, vary with the type of load, the distance which it is carried, and the efficiency of the system. In general, the loss will probably lie somewhere between 15 and 30 per cent. The same authority[1] shows for the preceding year a difference of 17.7 per cent between the total energy generated and that sold, of which probably not over 1 per cent can be attributed to energy used within the companies' own systems. If, for example, a system generates 300,000,000 kw.-hr. during the year, from 45,000,000 to 90,000,000 kw.-hr. will be lost in distributing it to the customers. At even ¾ cent per kilowatt-hour which is probably a low cost for systems with steam generation (including all charges up to the point of utilization) this loss would amount to $337,500 to $675,000 per year, a not insignificant amount.

These figures are not presented simply to show what is quite generally well known, *i.e.*, that a great deal of money is spent and a large part of the energy lost in distributing it. It is, rather, intended to bring out the fact that the system of distribution as a whole and the local distribution system in particular, are relatively large factors in the total cost of producing and selling electrical energy. As such, they warrant as much attention and engineering skill as are granted the other parts of the property. Energy cannot be distributed without losses and a large investment in the distribution system is to be expected but it is only the part of good judgment to see that the money is wisely

[1] *Electrical World*, Jan. 5, 1929.

spent and that the losses are not greater nor less than is consistent with economy.

There is often a tendency to neglect the distribution system from the standpoint of engineering. This is possibly due to the fact that it is more widely scattered and hence less evident than other parts of the system and that practical results obtained from engineering work on the distribution system are sometimes rather hard to exhibit concretely. A generating station or a transmission line are imposing evidences of large investment and it is relatively easy to check costs and efficiencies with considerable accuracy. The features of their design can be easily discerned and any economies effected can be readily transcribed into dollars. It would be inconceivable to build a large generating station without careful engineering throughout. The distribution system, however, is more likely to be thought of as a maze of wires and poles occupying our streets and back alleys; a necessary evil but one we would like to forget. It is so widespread, the loads carried are so diverse and so variable, and the energy sold is metered at so many different points, that any very definite exhibit of results accomplished is extremely difficult if not impossible. These factors have sometimes (especially in the past) caused the engineering on the distribution system to be slighted, left to the so-called "practical" man rather than the professional engineer. And yet it would seem that these very factors would point to the advisability of careful and accurate engineering study to reduce as far as possible the wastes due to uncertainties and "loose ends."

One rather important feature should be pointed out in this regard. The distribution system is the last link between the company and the customer. It is the one he sees every day on his street or in his backyard. It is also just as likely (if not more so) to be responsible for the "goodness" or "badness" of his service as any other part of the system. From the standpoint of public relations alone, a well-designed, up-to-date, efficient distribution system is an invaluable asset.

There are three general types of engineering design which are applicable to problems in connection with distribution systems. These may be designated for convenience as:

1. Electrical design.
2. Mechanical design.
3. Economical design.

All problems encountered cannot, of course, be characterized as specifically belonging to one or another of these classes, since probably more often than not a study from all three viewpoints is advisable. The considerations involved are quite likely to be more or less interrelated and the best engineering solution is only reached by taking account of all three in proper proportion, with due regard to the effect of each on the other. For example, a design may be good electrically and yet some other design may be just as good and be also much more economical. Economy in construction must be tempered by considerations of strength, safety, and minimum maintenance. The solution of any such problem will come nearest perfection as each of these forms of design is more soundly analyzed in connection with it, and the combination of the three more intelligently applied.

Electrical design deals chiefly with those features of a system, type of construction, or piece of apparatus which might affect its satisfactory operation. Viewed from the standpoint of *electrical design* only, anything which will accomplish successfully the results desired is acceptable. A distribution system which will transmit the necessary energy to the customer with the requisite provision for good service is a proper one, regardless of its cost, if *electrical design* only is considered. It is evident, however, that the considerations of cost usually do enter the problem in some form and to some extent. That is, an application of *economical design*, even if only casual, is usually essential.

Mechanical design involves the study of structures and apparatus. It includes the selection of proper materials and their combination into structures and these into systems in such a manner as to fulfill the requirements of *electrical design* and also give due consideration to matters of strength, safety, appearance, length of life, maintenance and other related factors.

Economical design is the investigation of relative costs. Where there is a possible choice of more than one design which would be satisfactory from the standpoint of *electrical design* and *mechanical design*, the final decision should be based on a careful study of relative economy. It should be clearly understood that this does not mean that first cost should be the deciding factor. Economy must involve the elements of low operating costs and yearly carrying charges, which are usually more important than first cost. Also, it should be emphasized that economy is not to

be urged at the expense of good service. The quality of service required is a factor in electrical design and this must, of course, be satisfied before economy may be considered. It is seldom, however, that any problem may be solved without some regard to the question of cost, whether it be merely the comparison of quoted prices or an involved study of annual charges over a period of years.

The three types of design, *electrical*, *mechanical* and *economical*, will be treated separately in this book, a section being devoted to each. Their interrelation is recognized and is pointed out from time to time, but the fundamental principles of each and their application to specific cases can be better shown by keeping them separate.

The subject of electrical distribution might be treated in several different ways. A great deal could be written on the historical development of the art and present practices. A book for the construction man or field man would be useful, giving to a large extent practical details of line construction and layout. In this work, however, the subject is approached rather from the viewpoint of the student or the design engineer. Present practices and construction details are, of course, included to a considerable degree, but the chief object has been to present as far as possible the underlying theory of the several types of design. Comparatively little has been included regarding the details of various makes or designs of different types of apparatus except where such details are of especial importance in connection with the design or operation of the distribution system as such. It is felt that if the basic theory is understood, the engineer has the most useful tool to apply in the solution of the various problems, new and old, which continually arise.

There, are, of course, many major problems concerning distribution systems for which a generally accepted "best solution" has not yet been reached. In such cases, it has been attempted to give as far as possible an impartial discussion of the factors affecting all sides of the question and the advantages and disadvantages of various proposed solutions without unduly stressing any one.

The general subject of engineering design of the distribution system is so large and the factors involved are so variable that it is obviously impossible to cover everything fully and in detail. It is hoped that the discussions and information given are such

as to be of the greatest use to the largest number. Overhead systems have been stressed somewhat at the expense of underground with the belief that by far the greater part of the distribution systems are overhead. Underground has been included to some extent, however, where essential to a complete picture of the subject.

Before proceeding to a detailed consideration of the details of design, it might be well to bring out one important factor which affects a large part of the problems encountered on the distribution system. That is the extreme variability of so many of the elements involved. Load (in general), load increase, location of loads (general), service requirements, mechanical loading (wind, ice, etc.), financial conditions, etc. are all quantities of considerably indefinite nature. It sometimes appears almost useless to attempt to reach a definite solution with the assumed conditions so prone to fluctuation. It should be remembered, however, that most of such variables are subject to reduction to averages of a more or less definite nature, and that results based on averages, if correctly reached and correctly used, cannot fail to have beneficial application. Even where such averages are undependable, the knowledge gained from an intensive study of the surrounding conditions and basic theory, place the engineer in a position to apply intelligently his good judgment to reach a solution which has all the chances of probability in its favor of being far more nearly correct than a mere guess. In a great deal of this work it is impracticable to make a complete study of each individual case of detail design. A study of averages, however, will lead to the establishment of certain standards which can be applied (with a little common sense) to individual problems of that class.

PART I
ELECTRICAL DESIGN

CHAPTER II

GENERAL CONSIDERATIONS

A knowledge of the electrical characteristics of distribution systems and the fundamental electrical theory underlying their study is, perhaps, the most essential requirement for one who would design such systems. The electrical features of load characteristics, voltage, voltage regulation, system arrangement, etc. are the first things to determine in laying out a new system, in revamping an old one, or in satisfactorily operating either. One of the chief features of problems of this kind is the variability of many of the factors involved. Loads, with few exceptions, fluctuate in amount from hour to hour during the day and from day to day during the year. Increase in load, while following certain general tendencies, is extremely difficult to forecast for small groups or limited localities. Service requirements in the way of continuity of service and voltage regulation are matters which, as a rule, are not clearly defined in any particular case. They depend not only on the actual needs of the customers served but also on the quality which they have been taught to expect and on considerations of public relations, company policy, etc. Quality of service is usually limited to some extent by economic conditions, the cost being more or less in proportion to the quality, whereas the return is not likely to be so influenced. All these factors and others of similarly variable nature enter into the problems of design on the distribution system. They call for the careful study of all the affecting conditions and the application of a considerable amount of good judgment on the part of the engineer as well as a knowledge of the technical details involved. It is very largely the acquirement of this element of good judgment, as applied to such problems, by study and experience, that makes the distinction between the novice and the trained distribution engineer. It should be emphasized however that, with the increasing size and density of systems and the complexity of the problems involved, a foundation of technical knowledge is also an essential in this work.

It has been assumed in the following discussion that the reader has a general knowledge of the fundamentals of electricity. In Chap. XIV, as a ready reference, are given briefly some of such fundamentals, general characteristics of electrical circuits, etc. which are particularly necessary and applicable to this work.

This section of the book (Part I) will deal with the design of the distribution system as a group of electrical circuits, giving, as far as possible, data and methods by which the ordinary problems arising in connection with such circuits may be attacked and solved. It will take up the various types of loads usually encountered and give the characteristics of each as they effect the distribution system necessary to carry them. It will discuss the various types of distribution systems in common use, both as to layout and as to voltage, phases, etc., giving advantages and disadvantages in the use of each. Finally, consideration will be given to some of the details of the design of individual circuits which affect their satisfactory operation, such as voltage drop, regulation, fusing, etc. Many of the electrical problems of design are so interrelated with considerations of mechanical and economical design that it is difficult to consider them separately but in such cases reference will be made to Part II on "Mechanical Design" or Part III, on "Economical Design" where those features of the problem will be discussed more fully.

CHAPTER III

LOADS AND THEIR CHARACTERISTICS—I. GENERAL CHARACTERISTICS

Before a distribution system or any part of it can be intelligently designed to carry a given load, it is essential that the characteristics of that load be known in so far as it is possible to determine or estimate them. A study of loads and their characteristics involves not only the different types of apparatus used and the grouping of such apparatus to form the load of an individual customer, but also the grouping of customers into typical composite loads, and the combining of such loads into still larger diversified groups. For example, the electric range should be studied, as a piece of apparatus which is quite commonly used. Its characteristics as an individual load should be understood. Further, its effect on the total load of the customer using it as part of his electrical equipment must be considered. Then residence load as a class must be studied, that is, the load imposed on a distribution circuit or part of one by a district distinctly residential in character and including a fair percentage of customers using electric ranges. Finally, attention must be given to composite loads drawn by larger areas, consisting of certain proportions of power load as well as residence load, perhaps, or of other characteristically different types. Such a load would be represented by the total load on a substation carrying both residence and power loads, street lighting, street railway, etc. Such groupings would also include total system loads, *i.e.*, loads on the generating plants. However, since this work is intended to apply more specifically to the distribution system in its restricted sense, it is not so particularly concerned with these larger groups of generating station and substation loads as with the individual customers and typical classes of loads.

Before proceeding with the study of particular types of loads, it is essential that an understanding be had of what are the important characteristics of a load and how, in general, they affect the design of the system. This chapter will deal with the chief

characteristics of loads with which we are concerned, defining and describing them in some detail.

Demand.—The size of any load, or its demand, is the maximum load, expressed in kilowatts (kw.) at a certain power factor, or in kilovolt-amperes (kv-a.), which is drawn from the source of supply at the receiving terminals, averaged over a suitable and specified interval of time.

The determination of the demand of any load or group of loads is of the highest importance since it is the demand which governs the size of conductors, transformers, etc. The interval of time chosen for measuring demand may be very small, such as 1 sec. or 1 min., for example (or even instantaneous peak), or it may be much larger, such as 10 or 15 min. or more. The choice of the

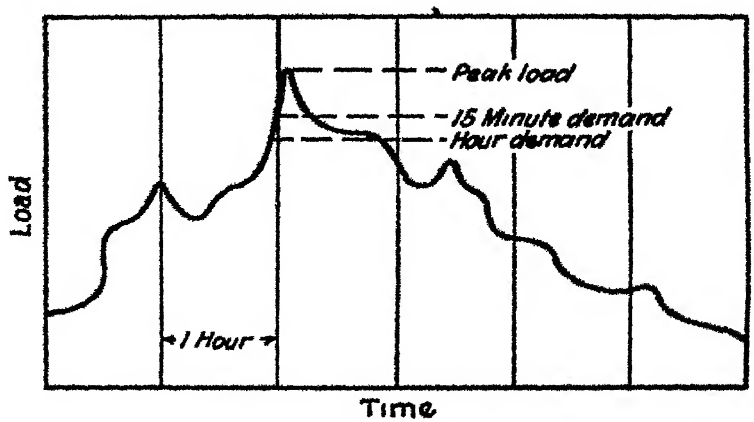

FIG. 2.—Demand.

proper interval will depend largely on how the demand figures are to be used or the part of the distribution system which is under consideration. For example, the starting current of an induction motor inflicts a sharp peak on the load curve. This peak is likely to be quite high in comparison with the steady running load, but is of but a few moments duration. If the motor comprises the major part of the load of the service on which it occurs and also on the transformer serving it, however, this starting current demand must be considered in determining the size of the transformer and of the service wiring. Otherwise this current will be likely to cause an excessive voltage dip and hence flicker in illumination from lamps connected on the same service. If, however, the motor is only one of a large number of similar

motors on the service, or its load is only a small percentage of the total load on the transformer, secondaries, or service wiring, the peak due to its starting current is of relatively less importance and is easily absorbed in the relatively large capacity of the transformer and wiring without causing an undue amount of voltage dip. In the latter case, a longer interval of time for determining demand is justified. The sharp peaks may then be neglected and only the current which would affect general voltage regulation or heating of transformer coils need be considered. A 10- or 15-min. interval is quite commonly used for such purposes and if heating of transformer coils only is the criterion, even a much longer interval may be satisfactory (refer to Chap. IX, Transformers).

Figure 2 shows an example of load curve illustrating the demand for several time intervals.

Demand Factor.—The distinction between *demand* and *connected load* on any service should be noted. Connected load is the total of the rated capacities of all electrical appliances, lamps, motors, etc. which are connected to the wiring of that service. The actual demand in nearly all cases is considerably less than the connected load due to the fact that different pieces of apparatus are used at different times, or, if used at the same time, their peak loads may not be simultaneous, or in either case all units may not be loaded to full capacity even at their peak load. The exception to this is on loads where all utilization apparatus is of the same general type and is used at the same time and to full capacity—street lighting, for example.

The ratio of maximum power demand to total connected load is called the "demand factor." For example, ten 5-hp. motors on one service may have an actual total demand of only 25 hp. instead of 50 hp. In this case, the demand factor = $25/50 = 1/2$ or 50 per cent.

As another example, assume a customer has a connected load of

	Kilowatts
100 40 watt lamps	4 0
Small motors, total connected	25.0
Heating apparatus, total	10.0
Total connected	39.0
Maximum demand	20 0
Demand factor $20/39$ =	0 513 or 51 3 per cent

Demand factor is usually applied to the demand of an individual customer but is sometimes used in connection with the load of a group. In such a case, however, it should not be confused with *diversity factor*.

The fact that a *demand factor* exists and is in many cases comparatively small is sometimes overlooked in determining the necessary equipment to serve a customer. Its recognition and use, even if only very roughly approximated, will sometimes lead to very marked economy and is always worth while.

Diversity Factor.—The diversity factor is the ratio of the sum of maximum power demands of the component parts of any load

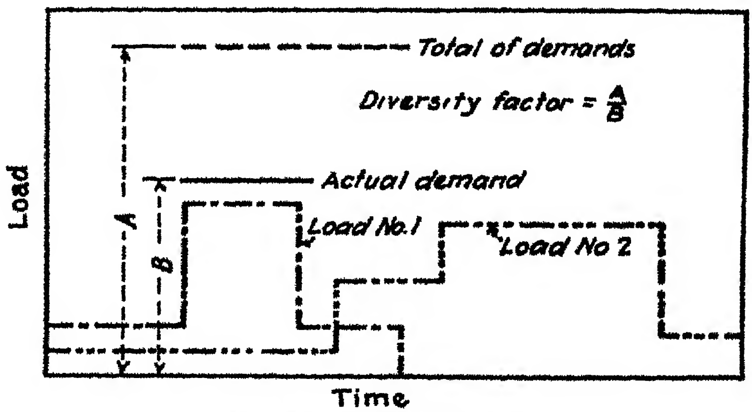

FIG. 3.—Diversity factor.

to the maximum demand of the load as a whole measured at the point of supply.

For example, a transformer may serve five customers, each with a maximum demand of 30 kv-a. Due to the fact that the maximum demands of all of the five do not come at the same time, the actual demand on the transformer may be only 75 kv-a. instead of 150 kv-a. In this case, the diversity factor = $^{150}/_{75}$ = 2. (It should be noted that *demand factor* is defined in such a way that it is always less than 1, *diversity factor* in such a way that it is always greater than 1, that is, the form of one is the reciprocal of that of the other.)

Such diversity is found between customers, between transformers, between feeders, between substations, etc. It can be used to marked advantage in reducing the required capacity of such parts of the system from that which would be necessary if

design were based on connected load or on the sum of component load demands only.

Figure 3 illustrates diversity factor. It will be noted that diversity factor is somewhat similar to demand factor except that the former deals with actual loads or demands and arises from the diversity in time of occurrence of loads or their maximums whereas the latter includes the effect of partially loaded or unused apparatus as well as diversity in use.

Load Factor.—Load factor is the ratio of the average power for a certain stipulated period of time, such as a day, a month, or a year, to the maximum power or demand for a short interval

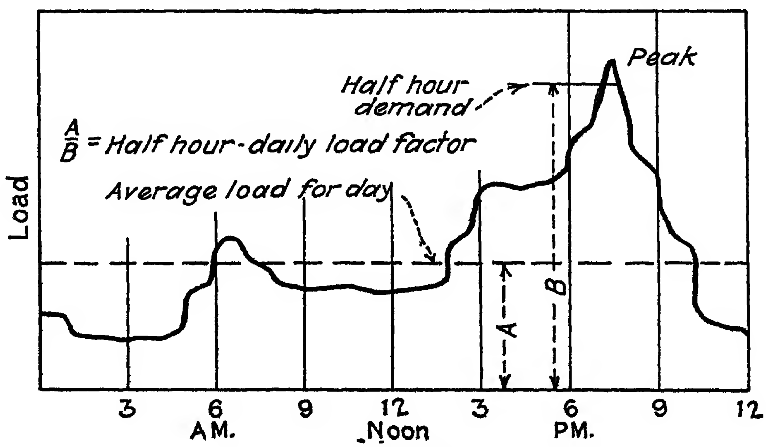

Fig. 4.—Load factor.

of time (see above definition of demand) during the same period. In referring to the *load factor* in any particular case, both the interval of time for the maximum load or demand and also the period for which the average power is taken should be specified. For example "half-hour-monthly" or "15-min.-daily" load factors are spoken of. Expressed mathematically,

$$\text{load factor} = \frac{\int_0^t w\,dt}{W \cdot t},$$

where

w = the load at any instant.
W = the maximum load.
t = the period of time chosen.

Figure 4 illustrates load factor for an arbitrarily assumed load curve.

In dealing with problems concerning the distribution system, load factor is, of itself, usually not as important as the whole

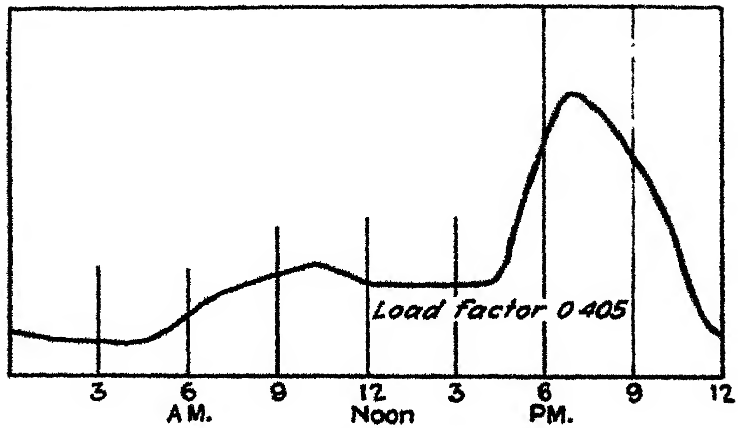

Fig. 5. Typical daily lighting load (system).

load curve from which it is derived, *i.e.*, the curve showing the fluctuations of the load from hour to hour or from day to day throughout the period under consideration. Such a load curve is illustrated in Fig. 4, which is just an arbitrarily assumed example and does not refer to any particular kind of load, also in

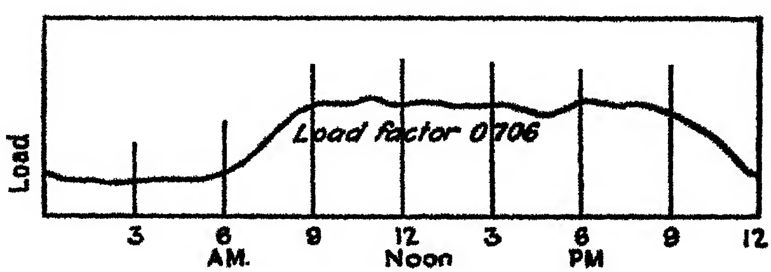

Fig. 6.—Typical daily downtown commercial load.

Figs. 5, 6, 7, 8, 9, and 10 for typical classes of loads. *Load factor* is an index of the efficiency with which the system or portion of the system under consideration is utilized, 100 per cent load factor or 24 hr. per day operation at peak load being the maximum possible. The actual peak load or maximum demand, however,

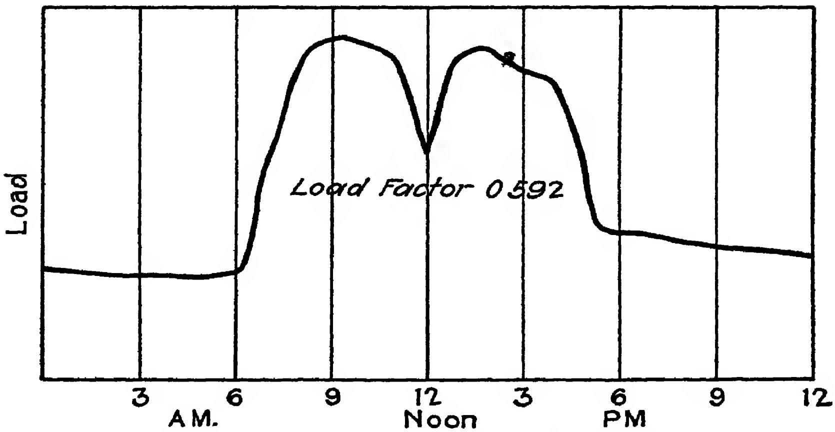

FIG 7.—Typical daily power load (system)

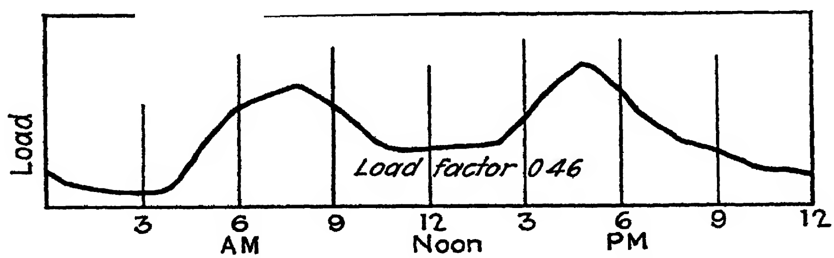

FIG. 8.—Typical daily street-railway load.

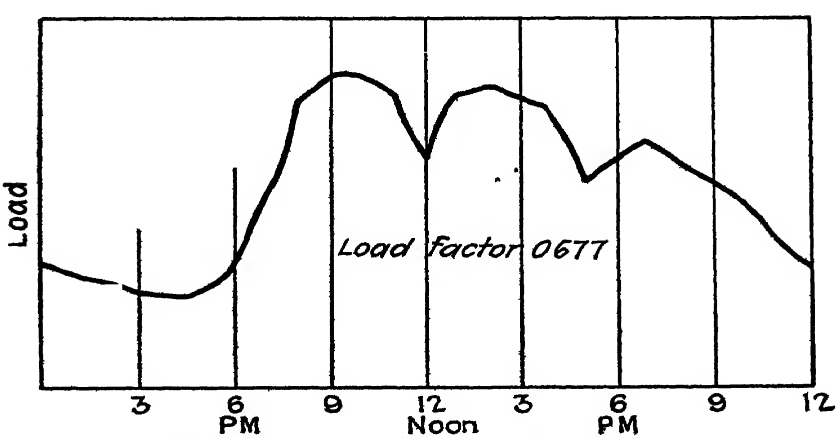

FIG. 9.—Typical daily total system load.

and the relative amounts of load at other times throughout the day or year whereby energy losses may be determined, are factors which it is necessary to know for an intelligent study of any specific problem.

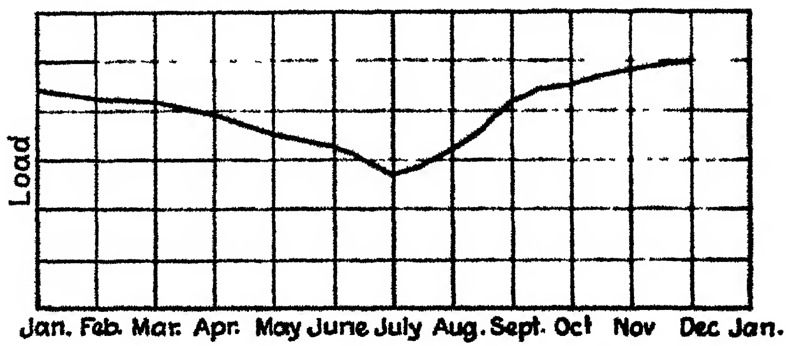

FIG. 10.—Typical yearly general distribution load.

Loss Factor.—Loss factor is a term not so generally accepted as a standard as some of the others discussed here, but it denotes a characteristic of any load which it is essential to understand in working with energy losses and cost of such losses.

It may be defined as the ratio of average power loss for a certain stipulated period of time, such as a day, a month, or a year, to the maximum loss or loss at peak load (for a short interval of time) during the same period. The interval of time corresponding to the peak load and the period over which the average loss is taken should be specified, for example "half-hour-monthly" loss factor.

It will be noted that loss factor is very similar in definition to load factor. In fact, the two correspond quite closely and, for certain types of load curves, have the same value. For this reason load factor is often wrongly used in place of loss factor in dealing with power losses. The distinction between the two lies in the fact that load factor pertains to *loads* (maximum and average) while loss factor pertains to *losses* which are proportional to the square of the corresponding loads.

$$\text{Loss factor} = \frac{\int_0^t i^2 r\,dt}{I^2 r t} = \frac{\int_0^t i^2\,dt}{I^2 t}$$

where

i = current at any time.
I = the peak current.
t = the period of time chosen.
r = the resistance of the circuit.

Figure 11 illustrates the relation between loads and losses and between load factor and loss factor for a simple arbitrarily assumed load curve.

Loss factor is used in determining total power losses for a given period for a load whose peak value and loss factor are known.

Total losses = $I^2r \times 24 \times$ loss factor, for a given day.

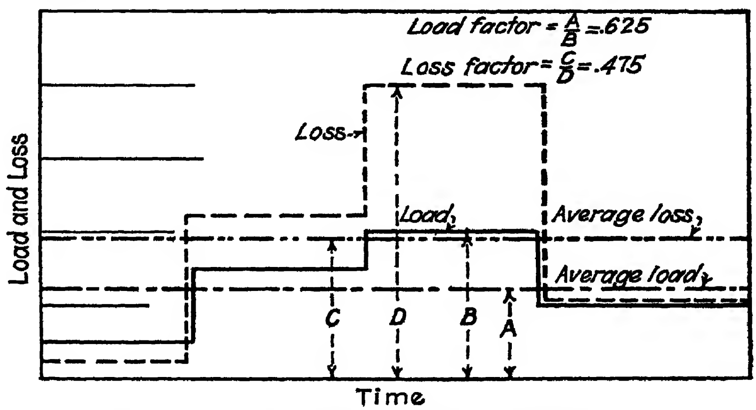

Fig 11.—Load; loss, load factor, loss factor.

For example, assume a load of 100 amp., a resistance of 1 ohm, a loss factor of 20 per cent.

Total losses = $100 \times 100 \times 1 \times 24 \times 0.20$ = 48,000 watt-hr. or 48 kw.-hr. per day.

Loss factor may have any value between the extreme limits of being equal to load factor and to (load factor)^2. This may be demonstrated as follows:

1. An extreme case would be a load for which the peak is sustained throughout the whole period during which there is any load. At all other times the load is 0. This condition is found with such loads as street-lighting circuits and motors driving constant loads, and is approached by the characteristic power load on a large system. Figure 12 illustrates such a load. In this case,

$$\text{Load factor} = \frac{W \times t_1}{24 \times W} = \frac{t_1}{24},$$

where

t_1 = the number of hours for which the load is on.
W = the load in watts.

$$\text{Loss factor} = \frac{I^2 r t_1}{I^2 r \times 24} = \frac{t_1}{24} = \text{load factor.}$$

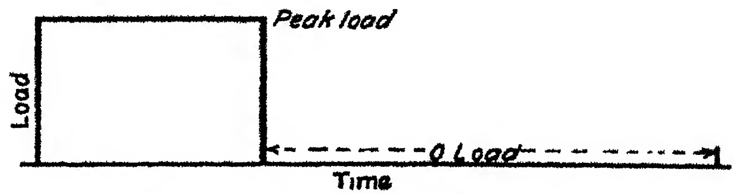

FIG. 12. Loss factor—sustained peak.

2. The other extreme is a load with a peak of very short duration, the load curve being flat for the remainder of the day. This condition is approached by characteristic residence-lighting load. Figure 13 illustrates such a load. In this case,

$$\text{Load factor} = \frac{w}{W}$$

(t, in this case, = 24 hr.),

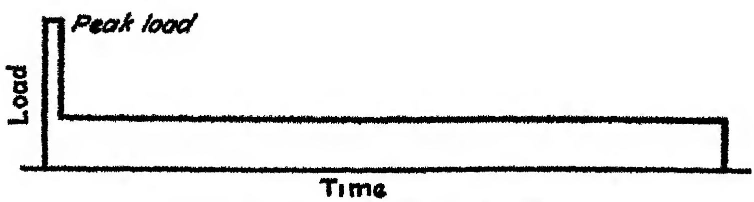

FIG. 13.—Loss factor—short peak.

where

w = the average or continuous load.
W = the short-time peak.

$$\text{Loss factor} = \frac{i^2 r}{I^2 r} = \frac{i^2}{I^2}$$

where

i = current corresponding to w.
I = current corresponding to W.

$$\frac{w}{W} = \frac{i}{I}.$$

$$\text{Loss factor} = (\text{load factor})^2.$$

These are the limiting cases since no more efficient distribution of load for a given peak and given total energy can be made than

in the second case and no less efficient than in the first case. The general rule may therefore be stated that the value of *loss factor* always lies somewhere between that of *load factor* and (*load factor*)^2. For most practical cases of actual loads, the value is usually not close to either limit but rather at some intermediate value, being nearer load factor for power loads where the peak is fairly flat, and nearer (load factor)^2 for lighting loads where the peak is sharp and of short duration. This rule is useful in approximating the value of loss factor when the type of load is known but an accurate determination of loss factor is not practicable. For example, a characteristic lighting load with a load factor of 20 per cent would have a loss factor between 4 and 20 per cent and nearer 4 per cent. Probably its actual value would be in the neighborhood of 7 or 8 per cent, depending, of course, on the shape of the load curve.

A useful corollary to loss factor is a quantity which may be called "equivalent hours." It is defined as the average number of hours per day which the peak load would have to continue to give the same total energy loss as that given by the variable load (throughout the year, month, or week as the case may be).

Equivalent hours = loss factor × 24.

A further discussion of losses and loss factor will be found in Chap. XI.

Power Factor.—Power factor is the ratio of power (in watts or kilowatts) to the product of the voltage and the current (in volt-amperes or kilovolt-amperes). It is sometimes defined as the ratio of real power to apparent power. For currents and voltages of sine-wave characteristics, the power factor is equal to the cosine of the angle representing their difference in phase.

$$\text{Power factor} = \cos\theta = \frac{\text{watts}}{EI},$$

where

E = effective voltage.
I = effective current.

Figure 14 illustrates the relation between current and voltage out of phase with each other, instantaneous power, and vector representation of these quantities.

When loads are designated in *kilowatts* it is essential to know the *power factor* also, since capacities of transformers, etc. which depend on allowable heating of coils, are rated in kilovolt-amperes.

Also, line losses are proportional to the square of the current, and voltage drop to the current (approximately). The value of high power factor, which gives a minimum current for a given amount of actual useful power, is especially evident on the distribution system, the design of which is so largely dependent on *current* capacity. For the same current and the same voltage, the power delivered is directly proportional to the power factor.

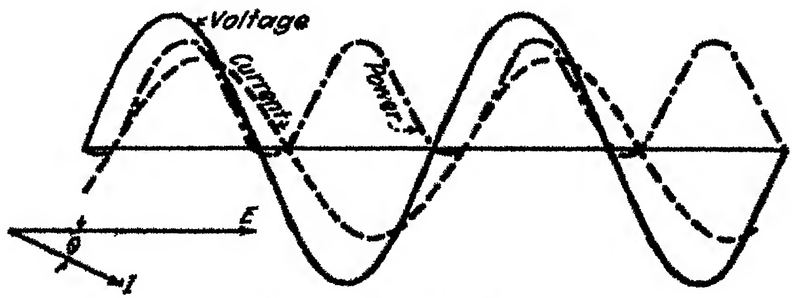

Fig. 14.—Power factor.

Balance.—When polyphase circuits are employed, the loads on the various phases are likely to be unequal. If single-phase loads are carried, it is ordinarily very difficult to obtain and maintain a perfect division of loads among the phases. Unbalanced or unequal currents produce unequal voltage drops in lines, transformers, etc., thereby occasioning unbalanced voltages at the loads. Unbalance in voltage tends to aggravate the condition by producing unbalance currents in polyphase motors connected.

The expression of unbalance by a simple percentage or *balance factor*, while desirable, is difficult to accomplish in such a way as to completely describe the condition. Unbalance in voltage is sometimes expressed as the maximum divergence of any phase from the voltage of all the phase voltages, expressed in percentage of the average phase voltage. For example, a three-phase system with 112, 115, and 117 volts across the three phases would be said to have an unbalance of $\frac{114.7 - 112}{114.7} = 2.35$ per cent. This method does not indicate phase relations but under certain conditions it serves as a convenient measure of unbalance. As a rule, in distribution problems we are more interested in actual currents and voltages than in a composite expression of unbalance.

On three-wire, single-phase, or direct-current circuits, unbalance also frequently occurs between the loads on the two sides of the circuit, leading to unbalanced voltages.

Load Distribution and Load Density.—An individual customer's load, as it commonly occurs on a distribution system, may be considered as a *concentrated* load in relation to that system. That is, it is connected to the system at one point and up to that point—the service connection—it acts as a unified load no matter how it may be subdivided within the service. A group of individual loads, such as a block of residences, may produce a composite load scattered along a line which for the purpose of

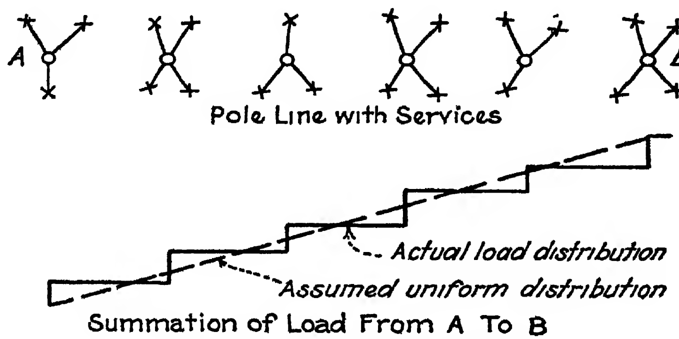

FIG. 15 —Distributed loading.

design may be conveniently considered as a more or less uniformly *distributed* load. The services may be connected in groups, a few at each pole, for example, but if they are of nearly the same size and type, it is usually easier to treat the whole load as if uniformly distributed along the line (see Fig. 15). In most cases the error introduced is negligible, although there are certain problems in which it is preferable to deal with each point of connection as a point of concentrated loading. Distributed loading may be applied to load connected along a secondary main, to transformer loads connected along a primary main in some cases, and also to total loads distributed over larger areas such as the area served by a substation.

Most problems involving uniformly distributed loading, are simplified by converting them into their equivalent in concentrated loading. Power loss over a line on which the load is uniformly distributed from the source to the end of the line is equivalent to the loss which would be occasioned by the total load con-

centrated at a point one-third the distance. Voltage drop to the extreme end of such a line is equivalent to that which would be occasioned by the total load concentrated at one-half the distance. These points will be discussed further in Chaps. X and XI.

In practice, loads of a different type and size will sometimes be superimposed on a group which otherwise can be considered as a uniformly distributed load. These may be dealt with as individual concentrated loads added to the uniformly distributed load of the line. Such a case, for example, would be a large apartment house in a district otherwise built up with small and medium-sized single residences.

When speaking of distributed loads, the term "load density" is commonly used to describe their magnitude. The terminology of load density has been defined by the National Electric Light Association as follows:[1]

"Load density shall be given in terms of kilovolt-amperes per 1,000 ft. or in terms of kilovolt-amperes per square mile."

The former designation is useful when considering small units of the system such as the load on a secondary main along a street or alley. The latter form is more applicable to larger subdivisions of the system, such as the load in a given area, on a substation, or on the system as a whole.

Load Growth.—One of the most important questions to be considered in planning a distribution system is the probable future growth of the loads. It is the rare case where a system can be designed on the basis of present loads only. As a rule, some growth at least is expected. This must be provided for either by spare capacity in the present design, or by provisions for possible future additions, or alterations, or both.

Load growth, in general, is attributable to several factors. New territory may be added, new customers taken on in old territory, and the load of old customers will increase. These factors are variously applicable to different parts of the system and in different degrees so that the assumption of any general estimate of load growth to fit all cases is impracticable. It has been the experience of the industry, as a whole, that the load has increased from 10 per cent to 15 per cent per year for quite a long period. This rate of growth cannot be assured for any length of time to come neither is it applicable to any particular locality. Load

[1] Electrical Apparatus Committee *Report*, N.E.L.A., *Annual Proceedings*, 1925.

growth is affected by local conditions to a large degree—general business conditions from year to year, status of the power company in its relations with the public, local habits, activity of the sales force, etc. The growths on various parts of a system will, in general, also be quite different from each other and from that of the system as a whole. It may be said that only a careful and continuous study of the various factors affecting load growth on all parts of the system under consideration will give the designer a proper basis on which to estimate probable future growth and, even so, the problem is a difficult one and impossible of solution with any great degree of accuracy

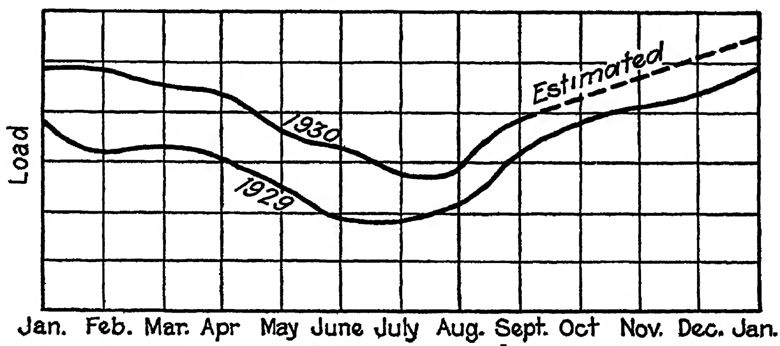

Fig. 16.—Load prediction.

Certain records of past performances kept from year to year and month to month, will be of considerable assistance in formulating predictions for the future. Some of these are:

Total system load.
Total loads of various types—lighting, power, etc.
Loads on substations.
Loads on individual distribution circuits.
Yearly tests on distribution transformers.
Number of men employed in industries connected to the system.
Volume of new buildings proposed.

With such records as these available, a reasonable estimate can usually be formulated which may be too high one year and too low another, but at least is more likely to be right than a mere guess.

Figure 16 indicates how a past year's curve may be used to aid in projecting the current year's curve to the peak period.

Just how far future load should be anticipated in installing present capacity is largely an economic question. It involves

a consideration of the cost of carrying the excess capacity until it is needed versus the cost of replacing smaller units with larger when it becomes necessary. The use of a limited number of standard sizes of various materials and equipment is also involved so that the most economical condition theoretically can only be approximated at best. No general rules can be laid down. With slow-growing load it is generally unwise to provide a large percentage of excess capacity since the exact nature or size of the load at any particular time in the distant future is usually very uncertain. Four or five years at most may be a long enough period to anticipate. With rapidly growing loads, on the other hand, care must be taken not to be too conservative or replacement costs at frequent intervals may far exceed the extra cost of additional capacity for a short time. In such cases, the rate of growth is more likely to be uncertain, also the percentage of spare capacity to provide for a long period will be much greater, hence a shorter period than that advisable for slower growing loads will usually be economical, 2 or 3 years possibly instead of 4 or 5. A thorough understanding of relative costs will be of great advantage in such studies.

Voltage Requirements.—Voltages for low-voltage utilization apparatus have been quite well standardized in this country at $^{115}/_{230}$ volts (with allowable departures of $^{110}/_{220}$ volts and $^{120}/_{240}$ volts) for lamps, appliances, and other single-phase apparatus, and 220 and 440 volts for polyphase motors. The greater part of the load on a general distribution system will usually be of this class. For any such system, definite standards of service voltage, the fewer the better, are essential. For example, $^{115}/_{230}$ may be established as the system standard for single-phase, with 230 for polyphase power and it be required that all low-voltage utilization apparatus connected be able to operate satisfactorily at these voltages.

Higher voltage apparatus, such as 2,200- or 4,400-volt motors, is used to some extent but is usually not numerous in systems of general distribution, having its special fields in particularly large industries. Such large customers are usually served at primary voltages, being responsible for their own secondary distribution and utilization voltage standards.

Allowable variation in voltage for any type of service is sometimes fixed by regulations of the state or other authority but in any case is limited practically by the range through which

the connected apparatus can operate satisfactorily and the fluctuations in illumination which can be endured. Good voltage maintained at the service is a most effective stimulant of public goodwill toward the utility. Economically, the effect of low or high voltage on revenue must also be considered as, for some loads, low voltage means a distinct loss in revenue.

The general subject of system voltages is discussed in more detail in Chap. X.

Continuity of Service.—For certain loads, absolute reliability of service is practically essential—even a short interruption is very disturbing and may lead to serious consequences. Such loads are hospitals, theaters, large department stores, large hotels, etc. For some other types of loads a high degree of reliability is very desirable though perhaps not quite so essential from the point of view of safety for the public. Examples of this are apartment buildings (some of these come in the previous class), and certain types of manufacturing load such as paper mills, where a shutdown of any appreciable duration may mean a large waste of material in process of manufacture. To the average residential or commercial customer, however, a short interruption or even an occasional fairly long one is more of the nature of an inconvenience than a serious hazard. His attitude in the matter is likely to depend somewhat on the reliability of service to which he has been accustomed. Rural customers and small outlying communities fed by long overhead lines are usually subject to a considerable number of outages and the requirements of the service are ordinarily such that no serious inconvenience results.

From the power company's point of view, interruptions of any kind at any time are undesirable. They produce loss of revenue and a certain amount of dissatisfaction among its customers as well as necessitating extra expenditures for the patrolling, repairs, replacement of equipment, etc. which is usually involved. It is entirely possible to give any customer essentially 100 per cent reliability if such is considered necessary. The expenditure necessary to provide such reliability, however, may be out of all proportion to the need for such service. As a rule, provisions for a high degree of continuity of service involve additional costs above those required to install the ordinary radial feed, the amount depending on the size and other characteristics of the load and its location relative to the sources of supply and other

loads. The feasibility of supplying such service depends on the relation between the additional expenditure and the demand or necessity for such service. For example, in a densely loaded downtown area, reliability approaching 100 per cent is a requisite and is comparatively easy to establish at a reasonable cost in view of the monetary return from such loading. In a rural district it is not essential, would be difficult to provide, and the cost would be relatively excessive.

CHAPTER IV

LOADS AND THEIR CHARACTERISTICS—II. TYPES AND CLASSES OF LOADS

In the previous chapter, the more important characteristics to be considered in connection with the loads on a distribution system were defined and discussed in a general way. Individual types and classes of loads generally encountered on such a system will now be taken up and the particular characteristics of each described. The greater majority of loads on a system of general distribution are composite, that is, they are made up of various individual elements which may differ more or less widely from each other. One customer's load for example, comprises lamps, appliances, motors, etc.; the load on a district includes both lighting and power loads, etc. Some of the most common smaller units will be discussed first, then the larger composite classes of load will be considered. A complete discussion of all types of loads can by no means be attempted. It is only intended to touch on the more important and these, for the most part, only in so far as they affect the design of the distribution system. Much of the data given, especially concerning composite loads, must be considered only as approximate or somewhere near the average. As applied to any particular case it must be qualified by good judgment and a knowledge of local conditions.

Lamps.—Lamps form a part of nearly all customers' loads since artificial illumination, for a part of the day at least, is necessary in connection with nearly all pursuits of life.

The most commonly used lamp for general illumination purposes is the incandescent lamp of the tungsten filament type. Carbon filament lamps, which preceded the tungsten type, still are used to quite a considerable extent. The tungsten filament is somewhat more fragile than that of the carbon lamp, hence the ordinary tungsten lamp is not quite so well suited to use in locations subject to vibration or shock as the carbon lamp. Special tungsten filament lamps have been developed, however,

to the point where they can supplant the carbon lamp in nearly all kinds of service with satisfactory results and greater economy. Other types of lamps, such as the mercury-arc lamp for factory illumination, and special lamps for various uses, have some vogue, but their total is small compared with the incandescent lamp. Arc lamps were formerly used extensively for street lighting but the incandescent is now, in general, more popular for that purpose.

The incandescent lamp ordinarily used for lighting home, office, or factory is usually of the type adapted to multiple circuits of the order of 115 volts (110 to 125 volts). According to the Lamp Committee of the National Electric Lamp Association, the present use of such lamps is divided into about 12 per cent of 110-volt rating, 48 per cent of 115-volt, 35 per cent of 120-volt, and 5 per cent of all other voltage ratings with a continuing trend toward the 115- and 120-volt classes. The lamps used at voltages of the order of 230 volts are only about 3 per cent of those used in the lower voltage class (115 volts, etc.). For street lighting, series-type lamps are quite commonly used although the multiple type also has considerable use.

In size, the lamp used for general lighting ranges from 10 watts up to 1,000 watts, with the sizes from 25 to 100 watts in the large majority. Standard ratings are 15, 25, 40, 50, 60, and 100 watts.

Street-lighting lamps are now generally rated according to illuminating value, *i.e.*, in lumens, rather than by wattage. Standard ratings are 400, 600, 800, 1,000, 2,500, 4,000, 6,000, 10,000, and 15,000 lumens. The majority of series-circuit lamps up to 4,000 lumens are made for 6.6-amp. circuits, 4.0 amp., 5.5 amp., and 7.5 amp. having also some use but being much in the minority. The larger sizes, 6,000 to 15,000 lumens, are mostly made for operation at 15 or 20 amp., being connected to the lower ampere operating circuits by small transformers or compensators. The wattage of the load drawn by series-circuit lamps depends somewhat on the type of circuit, transformers used, etc., and will be discussed later under street-lighting load.

Lamp load of itself shows no diversity between individual units (lamps) when in operation since the load of each lamp is essentially constant while it is in use. There is likely to be considerable diversity in use, however, especially in residence lighting where only a comparatively small proportion of the total number of lamps connected is ordinarily used at any one time.

The *load factor* of lamp load may be almost any amount from a very small value for lamps which are used only occasionally up to 100 per cent where they are used continuously. For the ordinary residence, the lamp load factor is rather low (probably not over 10 to 15 per cent on a yearly basis) since illumination is required for only a comparatively small portion of the day. In stores and offices it will run somewhat higher as a rule due to greater daytime use. Street-lighting lamp load has usually a fairly high load factor especially where all-night lighting is practiced (of the order of 50 per cent).

Power factor for incandescent lamps is practically unity.

Lamps of the 115-volt type are ordinarily connected across single-phase, two-wire circuits, such circuits being balanced on the two sides of a three-wire, single-phase circuit either at the customer's distribution panel or on the secondary mains outside, according to the size of the load. Sometimes, for very small loads, the two-wire circuit only is used from the transformer. The maintenance of a good balance on the two sides of the circuit, not only of connected load but also under actual operating load, is essential to good service. When connected to polyphase circuits, lamps, being single-phase devices, must be either carried on one phase only or else balanced among the phases. As a rule, the lamps are carried on single-phase circuits in such cases and balancing accomplished either by connecting these circuits to different phases at the service point or by balancing larger blocks of such load on the different phases of the distribution circuit. These points will be discussed more fully in later chapters.

The tungsten filament lamp has the property of taking somewhat greater current when cold, *i.e.*, when first turned on, than when heated. This is due to the fact that it has a positive temperature coefficient of resistance, its resistance becoming greater as its temperature is increased. In this it differs from the carbon filament lamp which has a negative coefficient. The rush of current through a cold lamp is so small, comparatively, as to be generally disregarded in considering individual lamps. With large groups of lamps, however, it may become important, for example in its effect on relay settings for automatic reclosing circuit breakers on distribution circuits. The effect of the positive temperature coefficient of resistance is quite important, however, in its relation to voltage variations. The current taken by the ordinary lamp varies approximately as the 0.58 power of

the voltage applied. A reduction of voltage below normal does not effect a proportional reduction in current, but only a reduction roughly in proportion to the square root of the voltage. Similarly with voltage increase, the current increases only as the 0.58 power, not in direct proportion.

$$\frac{I_1}{I_2} = \left(\frac{E_1}{E_2}\right)^{0.58}.$$

It follows that the wattage absorbed by the lamp is proportional to the 1.58 power of the voltage.

$$\frac{W_1}{W_2} = \frac{E_1 I_1}{E_2 I_2} = \left(\frac{E_1}{E_2}\right)^{1.58}.$$

For example, a 100-watt lamp at 115 volts would take a current of 0.87 amp. At 100 volts, the amperage would be

$$I = 0.87(^{100}\!/_{115})^{0.58} = 0.802 \text{ amp.}$$
$$W = 100(^{100}\!/_{115})^{1.58} = 80.2 \text{ watts.}$$

The luminosity of the lamp varies with the 3.51 power of the voltage for a tungsten lamp. This is somewhat lower than the figure for carbon lamps, that is, the variation in illumination is less with the tungsten lamp for the same variation in voltage.

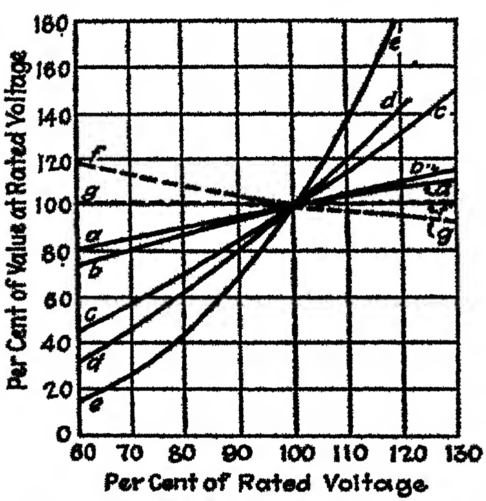

FIG. 17.—Characteristics of tungsten lamps: (a) resistance in ohms; (b) current in amperes; (c) power in watts; (d) efficiency in lumens per watt; (e) luminosity in lumens; (f) resistance of untreated carbon filament; (g) resistance of treated carbon filament.

Figure 17 shows graphically the variation of resistance, current, power, efficiency, and luminosity of the tungsten lamp with variations in voltage, also variation in resistance of carbon filaments of the treated (Gem) and untreated types.

The effect of voltage variations on luminosity is most noticeable and troublesome in voltage dips caused by starting currents of motors connected to the same circuits. Tests to determine the

maximum allowable dip in voltage[1] show that the amount of voltage fluctuation which is noticeable or objectionable depends somewhat on the rate at which the voltage changes and on the frequency with which the flicker or dip occurs. In general, it may be said that a 2 per cent dip in voltage is not particularly noticeable or objectionable unless it occurs frequently (several times per hour); 1 per cent cannot be detected by the eye ordinarily, and dips of 5 or 6 per cent or even larger do not give rise to serious complaints if occurring only occasionally. About 3 per cent is usually accepted as a maximum allowable dip for good service conditions.

Series-circuit lamps are quite sensitive to variations in the amount of current flowing through the circuit. A variation of 1 per cent above or below normal should not be exceeded.

The life of lamps is dependent on the voltage applied, being considerably reduced at voltages appreciably above normal. The life also depends somewhat on the number of times the lamp is switched on and off.

Small Heating Appliances.—Small heating appliances are a large contributing factor to the comfort of the modern household and form a part of nearly all residence loads. They include flatirons, toasters, percolators, heating pads, waffle irons, heaters, curling irons, and an infinite number of other similar devices. Table I lists quite a number of these with their average demand. As a rule, these are probably more effective in increasing the consumption of current, *i.e.*, improving the load factor, than in adding to the load demand except in case of the larger units. Most of them are used more or less intermittently and at times of the day other than when the lighting peak is on, hence their load factor (of each unit individually) is usually extremely low and the diversity between various units very high. On any one service, the actual peak demand may be due to one or more of such appliances—a toaster or flatiron drawing 750 watts, if added to a certain amount of lighting, may well exceed the peak due to lighting alone. The high diversity and time of use, however, will cause the effect on the total demand of a group of such loads to be comparatively small. *Power factor* of such devices is practically unity.

[1] Kehoe, A. H., "Underground A.C. Networks," *Jour.* A.I.E.E., June, 1924; Williams, C. A., "Voltage Fluctuation and Its Effect upon Lighting," Pennsylvania Electric Association, Jan. 16, 1924.

TABLE I.—AVERAGE DEMANDS AND LOAD FACTORS ON ELECTRIC APPLIANCES[1]

	Average wattage	Annual load factor, percentage
Irons	525	1.3
Toasters	450	0.85
Grills	600	0.78
Chafing dishes	600	
Percolators	450	
Samovars	450	
Water heaters (lamp socket)	450	
Water heaters (over 650 watts)	2,500	
Milk warmers	440	
Sterilizers	450	
Heating pads	50	
Radiators (lamp socket)	600	
Radiators	1,000	
Radiators	2,000	
Radiators	3,000	
Vibrators and hair dryers	50	
Curling irons	20	
Sewing machines	75	
Lamp-socket motors	100	
Vacuum cleaners	160	1.7
Washing machines	175	0.75
Portable lamps	50	
Ranges	5,500	3.4
Ovens	600	
Buzz fans	60	8.8
Small stoves	500	
Dish washers	100	
Fireless cookers	660	
Tailors' irons	850	
Irons	3,000	
Glue pots	300	
Auto radiators	150	
Soldering irons	200	
Waffle irons	600	
Domestic refrigerating machines	300	33

[1] From N.E.L.A. *Bull.*, July, 1926.

Small heating appliances are generally rated at 115 volts but usually are so constructed as to permit them to be operated at voltages as high as 120 volts without shortening their life unduly. Being connected at such voltages (rather than at 220 to 240 volts), they are essentially an unbalanced load on the usual

three-wire, single-phase circuit. In this way they are similar to lamps but, being much larger and of more intermittent use, are less easy to balance with other loads on the opposite side of the circuit.

Close voltage regulation is not so essential for these devices as for lamps, since the effect of reduced voltage and its accompanying reduced current is merely to cause a corresponding reduction in the heat produced or a slowing down of the operation of the device. They are not nearly as sensitive in this effect as a lamp is in its illumination If poor regulation is allowed on such an appliance, however, its effect will be felt on lamps connected to the same circuit, causing them to blink noticeably when the heating device is turned on and possibly to burn low while it is on. Hence, it is important to keep the regulation within reasonably small limits for such devices which are used on the same circuits with lamps.

Resistance of such devices is practically constant, hence current varies directly in proportion to voltage and wattage consumed, also heat produced varies directly in proportion to voltage squared.

Water Heaters.—Electric water heaters, *i.e.*, tank heaters, cannot be said to have come into very general use although their use is growing as more efficient designs are placed on the market. As to characteristics as an electrical load, they are not essentially different from the smaller heating devices previously discussed except as to size. They draw usually from 1 to 5 kw. but balanced across the 230-volt circuit, at least in the larger sizes. Their load factor is not high but is much better than that for the smaller devices (probably of the order of 10 per cent). Ordinarily, for good service conditions, they should be connected on a separate circuit from the service entrance and not on the same circuit with lamps. Sufficiently good regulation up to the service entrance must therefore be maintained so that the lamps on other circuits will not be affected by voltage drop caused by the current in the heater.

The water heater is likely to be turned on at the time of the peak lighting load, especially if it is automatically operated, and hence may add to the peak demand of the customer and of the distribution circuit. There are devices on the market which can be used with a heater to automatically limit it to off-peak operation.

Electric Ranges.—The electric range has become quite an important load in some communities, especially in suburban

districts where gas service is not available. Even in large cities where gas is available, ranges are quite often found, especially in apartment houses with kitchenette apartments. In some localities the use of ranges is stimulated by a special rate for such service.

The connected load of a range varies with the number of heating elements contained and usually ranges from about 4 kw. for smaller ones to 7 or 8 kw. for larger, with some of still larger size in very large residences. (This does not include those for commercial use which may be much larger and must be considered as large individual loads.) The average is probably between 6 and 7 kw. Since the range is made up of several smaller units or elements, usually ranging from 500 to 2,000 watts in size, it is rather rare that the whole connected load is on at one time, especially for any appreciable length of time. The actual peak demand for the range will equal its total rating or connected load but this may be experienced only occasionally, the ordinary daily demand being perhaps only ½ to ⅔ as great and even that for short periods only. The diversity between several ranges in a group, under ordinary conditions of household use is therefore high. Tests made in various localities have indicated that the diversity factor (based on actual peak load, *i.e.*, rating of range) between three ranges is about 3, and increases to 5 to 7 for a large group—that is, 20 ranges or more. The average demand of a large group of ranges, 200 to 1,000 of various sizes has been given as 728 watts per range. It is safe to say that the average for even much smaller groups (over 20 ranges) will not be more than 1 kw. each.

The Domestic Range Committee, of the National Electric Light Association gives the following data on range load, obtained from tests in Washington and Oregon.[1]

	City	Rural
Average connected load	7.14	5.44
Average maximum demand	3.67	3.56
Maximum demand for group of 150 ranges:		
Summer	0.88	0.83
Winter	0.84	0.87
Annual consumption	1,424 kw.-hr.	1,424 kw.-hr.
Annual load factor	18.9	18.9

[1] N.E.L.A., Proc. 1927.

The peak on range load comes at about 6 p. m. as a rule (this will vary with localities and living habits) with minor peaks in the morning and at noon. The afternoon peak comes after the power peak (see Fig. 7) and before the lighting peak (see Fig. 5), hence does not usually add directly to the system peak but serves as a method of increasing system load factor. As affecting the local distribution system, the range peak for a few ranges may be less than the lighting peak and hence will add only a comparatively much smaller amount to that peak. For a number of ranges large compared with the lighting customers served, the range load may well predominate, since few groups of residence custom-

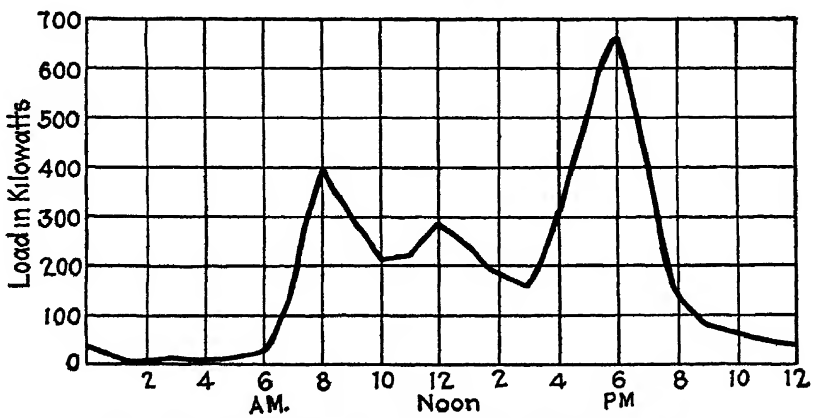

FIG. 18.—Typical daily load—1,000 electric ranges.

ers have an average lighting demand of anything like 1 kw. per customer. Figure 18 shows a typical daily load curve for range load, assuming 1,000 ranges.[1]

Load factor for a single range is very low, but for a group of ranges is much better, being somewhat of the same order as load factor for lighting load. An annual load factor of 4 per cent for a single range based on its peak demand and of 23.2 per cent for a large group (200 or over) based on the group demand has been found by test.[1] The demand does not vary greatly during the year except for a certain amount of decrease in use during the hotter summer months, usually not more than 20 per cent or so.

Power factor of range load is practically unity.

[1] SNOW, HARRY A., "Utility Research Indicates Appliance Load Values," *Electrical World*, Jan. 21, 1928.

The heating elements of a range are ordinarily rated at 110 volts (or thereabouts). They are usually connected so as to be balanced on the two sides of a 230-volt circuit as well as possible. It is a quite common practice to put the surface plates on one side and the oven elements on the other. This makes it a common occurrence to have all the load on one side of the line in operation at one time with no load on the other side. Such a condition of unbalance causes a large voltage drop on one side and a voltage rise on the other—an undesirable condition. Sometimes balance coils, or small autotransformers, are used on the service to balance such a load on the 230-volt circuit but the expense of these are not always justified. It is probably more common practice to provide for the unbalanced load by having the secondary and service wires large enough and the distance from the transformer not too great, the transformer also being of sufficient capacity. Perhaps somewhat greater regulation for the full range load than for lighting may be allowed. This may be permissible considering that the range is not often on, at least to anywhere near its full capacity, when the lighting peak is on. Since the half-load condition (all on one side of the line) is usually more serious in its effect on voltage regulation than full load, however, and such half load may under some conditions be an ordinary occurrence along with important lighting, care must be taken not to make too great an exception for range load, especially where close regulation on the lighting is important. Local conditions must be considered in judging this. In all cases the range should be on a separate circuit from the service entrance and not on a circuit carrying lighting.

As with smaller heating appliances, current varies practically in direct proportion to voltage applied; wattage consumed and heat output in proportion to voltage squared.

Small Motors.—Fractional horsepower motors are the motive power for vacuum cleaners, washing machines, electric refrigerators, electrically operated oil burners (furnaces), and similar equipment.

Common sizes are 1/6 and 1/4 hp. with some as small as 1/12 and 1/8 and some larger, up to 1/2 or 3/4 hp.

A very high diversity factor and low-load factor is obtained with such appliances as vacuum cleaners, washing machines, etc., whose use is only occasional and for comparatively short periods. Rarely do they add any appreciable amount to the

peak load of the customer or the circuit, their effect being chiefly an increase in consumption and hence in load factor. With refrigerators and oil burners, however, the case is somewhat different. They are usually operated automatically (thermo-

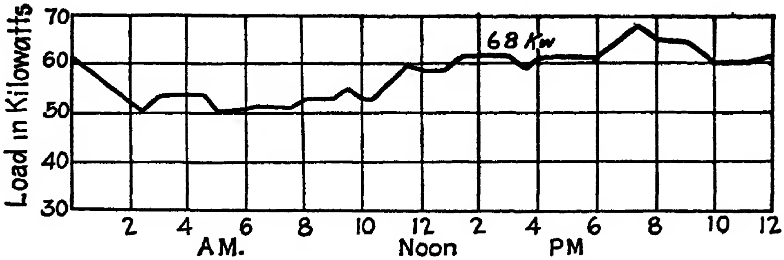

FIG 19.—Typical daily load—1,000 refrigerators.

statically) and are as likely to be operated at time of peak load as at any other time, thus adding directly to the peak. Since they are operated intermittently on a fairly constant mechanical load, their load factor is comparatively high and the diversity comparatively low. Tests made in Detroit[1] showed

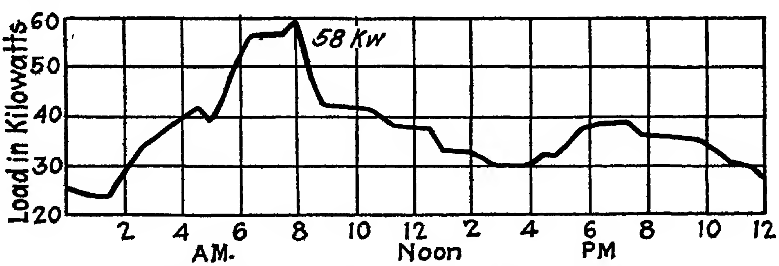

FIG. 20.—Typical daily load—1,000 oil burners.

For refrigerator load	Diversity between individuals	2.8
	Diversity between group maximum and assumed general December peak	1.61
	Annual load factor	69.3 per cent
For oil-burner load	Diversity between individuals	1.5
	Diversity between group maximum and assumed general December peak	2.
	Annual load factor—individual	17 1 per cent
	Annual load factor—group	25 4 per cent

Figures 19, 20, 21, 22 show typical daily and yearly load curves for these two types of load.

[1] SNOW, HARRY A., "Utility Research Indicates Appliance Load Values," *Electrical World*, Jan. 21, 1928.

The *power factor* of the majority of fractional-horsepower motors is low, from 50 per cent to 70 per cent with the average about 60 per cent. A general use of such equipment with low power factor, especially at time of lighting peak, is likely to become a serious problem to the power companies unless accompanied by a large use of ranges or other high power factor load.

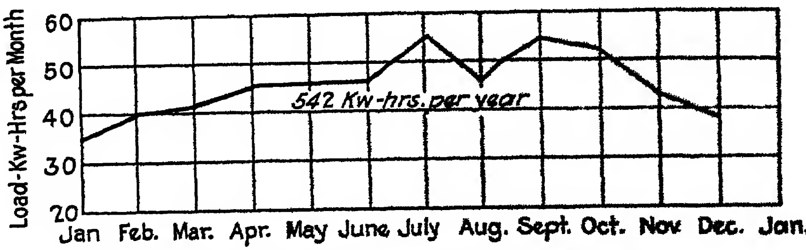

FIG. 21.—Typical yearly load—refrigerator.

This type of load is ordinarily rated at 115 volts, hence is unbalanced on the single-phase, three-wire system except as balanced by other loads on the opposite side of the neutral.

Good voltage regulation to the motor is not nearly as important as for lighting since the motor will run at a considerably reduced voltage (10 per cent or more). As with all other appliance load,

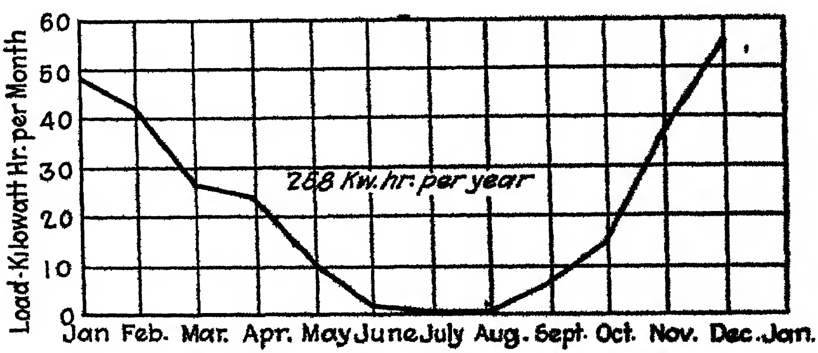

FIG. 22.—Typical yearly load—oil burner.

however, sufficiently good regulation should be maintained that the starting of the apparatus will not produce serious dips in the lighting on the same service. This is especially true of such loads as refrigerators and oil burners, which are on and off intermittently all through the day and night. If such regulation is provided, the requirements of the motor itself will usually be

amply taken care of. The starting currents of these fractional-horsepower motors are usually high, and these currents are at low power factors, hence they are quite likely to cause disturbance to the regulation of the service unless properly provided for.

It is interesting to note in this regard that the various interests concerned have recently agreed on standard limitations on fractional-horsepower motors as follows:[1]

Power factor (minimum)	From 50 per cent for 1/8 hp to 62 per cent for 3/4 hp. on short-use motors From 52 per cent for 1/8 hp to 65 per cent for 3/4 hp. for long-use motors
Locked rotor current (maximum)	20 amp. for 1/6 to 1/3 hp., 26.6 for 1/2 hp, 40 for 3/4 hp.
Three-fourths locked rotor current.	15 amp. for 1/6 to 1/3 hp., 20 amp. for 1/2, 30 for 3/4 hp.

Industrial Motors.—By far the greater number of electric motors used for commercial and industrial purposes are alternating-current motors of the induction type. Synchronous motors are used to some extent, however. Direct-current motors also have considerable use for purposes where accurate speed control is desirable, such as elevators and printing presses, not only in districts where direct current is the prevailing type of distribution but also in alternating-current districts with motor-generator connection. Little data of value can be given regarding the demand, diversity, or load factor of individual motors. Their size varies from fractional horsepower to very large sizes, and the type of load for which they are used, and degree of loading, determine the demand and load factor. The latter may vary from a very small quantity for intermittent loading up to 100 per cent for continuous operation at full load. The characteristics of groups of motors in certain industries will be considered later.

The *power factor* of an induction motor depends not only on its design but on the degree to which it is loaded. The power factor at full load may be almost any amount from 50 per cent to 95 per cent depending on the type and design, but ordinarily for the general run of motors (except fractional horsepower), the power factor is of the order of 80 to 90 per cent, the larger motors having somewhat the better values. When operated at less than full

[1] See *Electrical World*, Feb. 18, 1928, p 356.

load, however, the power factor drops appreciably approaching a very small value at no load. This condition sometimes becomes serious where a general policy of underloading or overmotoring is followed in a manufacturing plant. The power factor of the load as a whole will sometimes drop to values of the order of 50 to 60 per cent from this cause.

Synchronous motors can be operated at either a lagging or leading or 100 per cent power factor as desired by adjusting the excitation. If overexcited, they may be made to draw leading current and hence are sometimes used as condensers to correct the otherwise poor power factor of the induction-motor load of a plant.

The starting current of a motor often occasions a serious problem if the motor is connected on the same circuit or service with lighting load, especially if such load is of the order for which close regulation is considered essential. An elevator motor in an apartment house is an example of such a case. The starting current of an ordinary induction motor thrown directly in the line may run from two to six (or more) times the full load running current. This may be limited by starting devices or by special design. The comparatively large starting current causes a correspondingly large voltage drop or dip in the transformer and lines. If the motor is large compared with the lighting load, such dips may become a major factor in the design and transformer and secondaries have to be sized accordingly rather than for actual operating load. Sometimes the most satisfactory solution is a separate transformer and wiring for the motor. Primary voltage will be affected only in the most serious cases but it sometimes occurs that large motors, even if carried on separate transformers, will impair the service on a whole distribution circuit. Where the motor-starting current is small in comparison with full load on the transformer and secondaries, it will be absorbed without a noticeable dip and hence such a motor may be safely connected with lighting. Wiring to the motor from the customers' service entrance should be separate from lighting circuits as a rule.

Most of the larger motors used for general industrial loads are polyphase and even smaller ones also, down to 2 or 3 hp., where polyphase current is available. Polyphase motors are considerably cheaper as a rule than single-phase motors of the same size. Most of the power companies are making efforts to make

polyphase current available quite generally on their system, especially in commercial and apartment house districts.

Manufacturer's standard motor voltages are:

Single-phase 110, 220 volts
Polyphase, 110, 220, 440, 550, 2,200 volts.

The voltages most often encountered are 220 volts for single-phase over ½ hp and 220 or 440 volts for polyphase.

Voltage regulation to motors need not as a rule be of as high an order as for lighting except where lighting is also involved, as discussed above. The ordinary motor is guaranteed for "satisfactory operation at 10 per cent above or below rated voltage although not necessarily with the same characteristics as at rated voltage."

The current taken by a motor varies more or less in inverse proportion to the voltage applied, *i.e*, for a given load the product of voltage times current input will remain practically constant, except as the efficiency and power factor of the motor varies with voltage. The way in which the efficiency and power factor vary will depend considerably on the design of the motor and on the amount which the voltage deviates from rated voltage. For ordinary small fluctuations (10 per cent or less) the change in efficiency and power factor is usually inconsiderable.

Industrial Heating.—The field of industrial heating is one which has opened up comparatively recently but is rapidly assuming large proportions due to the relative ease of application and control of electric heat. The apparatus used is of three general types, welders, furnaces, and ovens.

The oven type (enameling, heat treating, baking, etc.) is a very desirable load from the engineering point of view. Ovens draw a fairly steady current at approximately unity power factor and are likely to have a high load factor, economical operation being continuous or nearly so.

Furnace load (brass, steel, etc.) on the other hand is likely to be more or less intermittent, drawing heavy "jumpy" current during part of the heat and lower current for the rest of it. On the whole, however, the load factor is likely to be fairly high, since economy points to as continuous operation as possible. The power factor of furnace load varies with the type of furnace from as low as 60 per cent to as high as 95 per cent, with probably the majority about 75 or 80 per cent. The sizes of electric fur-

naces vary through a wide scale. Three-phase steel furnaces often run from 1,000 to 2,000 kw. Brass furnaces are more often single phase, from 60 to 100 kw., but may be larger. Still smaller ones are found in other applications.

Welders draw an intermittent load of high peaks. Usually a welder is served at comparatively low voltage (30 to 50 volts) by a separate transformer off the main power circuit, having high current capacity. The larger sized welders may require use of a motor-generator set between the welder and the power system to prevent annoying voltage dips. The limiting size in such a case depends on the conditions of the case—type of lines, size, service requirements. In some cases it may run 200 or 300 kw., in others much less. The power factor of welder load is relatively low, varying through the weld somewhat and with the type of welder. The load factor of an individual welder is low, but for a large group of small welders it may be quite high due to the large diversity.

Residence Load—Light.—The composite load drawn by the more ordinary residence district, containing mostly one- and two-story residences, is usually made up quite largely of lamp load. Almost every residence will have a certain number of heating appliances and small motor appliances but the intermittent use of most of these prevents their adding greatly to the peak load which would be obtained from the lamps only. The exceptions to this are electric ranges, refrigerators, oil-burner motors, water heaters, etc. which have regular daily use and for a considerable part of the day. Such loads will add a considerable amount to the actual peak lamp load of any customer and, if occurring in any considerable proportion of the services in the district, will have material effect on the peak load of the district. Ranges and water heaters if generally used will predominate the lamp load and cause the actual peak, supplemented to some extent by the lamp load but usually at a different time than the lamp peak. Figure 23 shows a typical residence-lighting load curve (including small appliances) for 1,000 customers experienced in Detroit.[1] Figure 24 shows the effect on the group load if each customer had a range, a refrigerator, and an oil burner (see Figs. 18, 19, and 20 for these loads separately). Figure 25 shows the effect with range load only added to lighting. Under

[1] Snow, Harry A., "Utility Research Indicates Appliance Load Values," Electrical World, Jan. 21, 1928.

present conditions there are few localities where such composite loads as these illustrated will be found, the occurrence of such

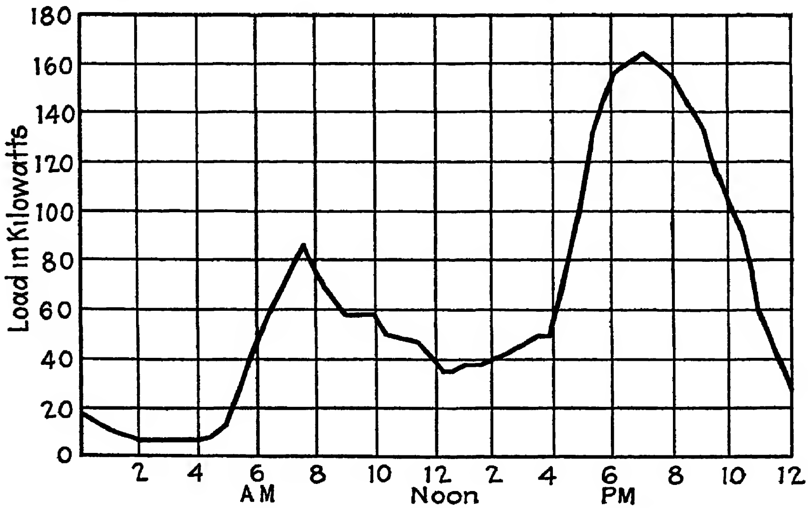

Fig. 23.—Typical daily load—1,000 customers, lighting and other uses.

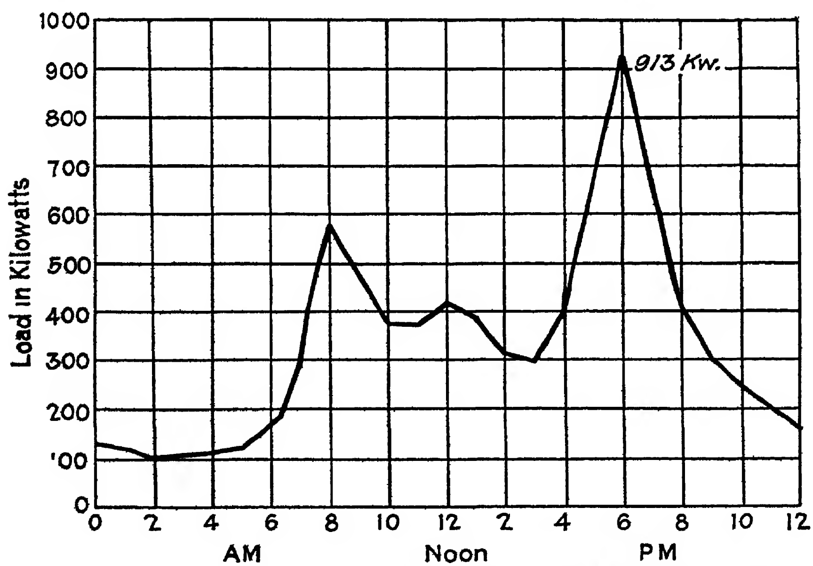

Fig. 24.—Typical daily load—1,000 residence customers with lighting, range, refrigerator, and oil burner.

appliances being more often occasional than universal. Their use is increasing, however. Where only an occasional range,

etc., is found, the net effect on the group load will depend on the proportion between total range load and total lamp load.

A high diversity is found between individual demands in a group of any considerable size—something of the order of 5 to 7—applying both to loads where lamps create the peak and also to those for which ranges predominate. For ranges the diversity will be of the order of 3 for a group of 3 or more up to 5 to 7 for a group of 20 or more (based on actual peak load, *i.e.*, capacity of range). The actual maximum demand for a residence will depend on the amount of appliance load and lamp load connected

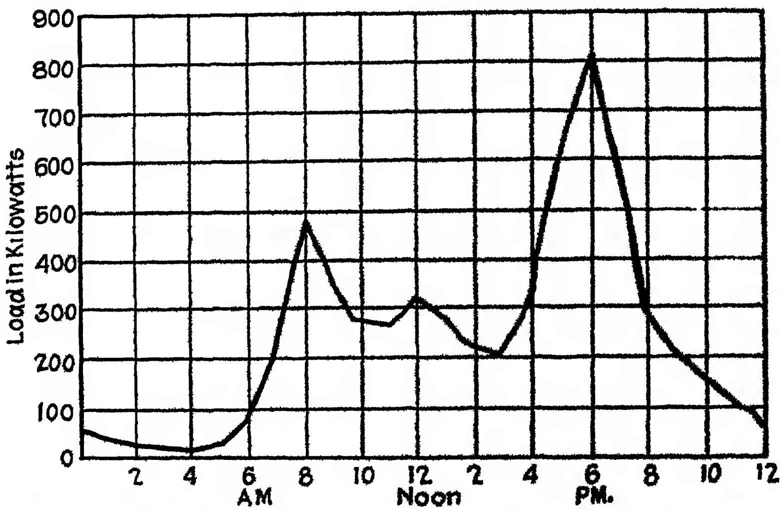

FIG. 25.—Typical daily load—1,000 residence customers with lighting and ranges.

and will run from perhaps 200 to 300 watts for small residences with no appliances, to 1 to 2 kw. for medium or large residences with small appliances, to 5 to 8 kw. where ranges are used. The following average loads for various types of load in groups of 40 or more customers were found in a test made in Detroit a few years ago—no ranges included:

	Watts
Very small houses	70
Medium-sized houses	300
Large houses	500
Two-family flats	180
Small stores	1,150

The load factor (annual) of the average residence load (group) is of the order of 20 to 35 per cent for lighting depending on the size and type of the group. When range load is added the load factor may or may not be increased, since the group range load factor is of somewhat the same order. In the example shown on

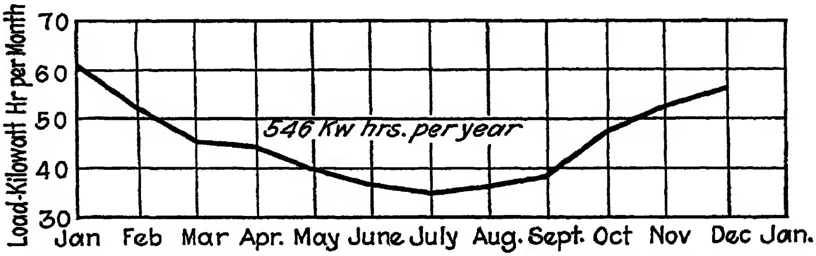

FIG. 26.—Typical yearly load—residence lighting and other uses.

the curves—Figs. 26 and 27 from the Detroit tests corresponding to the daily loads shown on Figs. 23 and 24, the yearly lighting load factor may be computed as 37.6 per cent while the addition of ranges, refrigerators, and oil burners for all customers gave a resultant load factor of 35.3 per cent. These figures should be

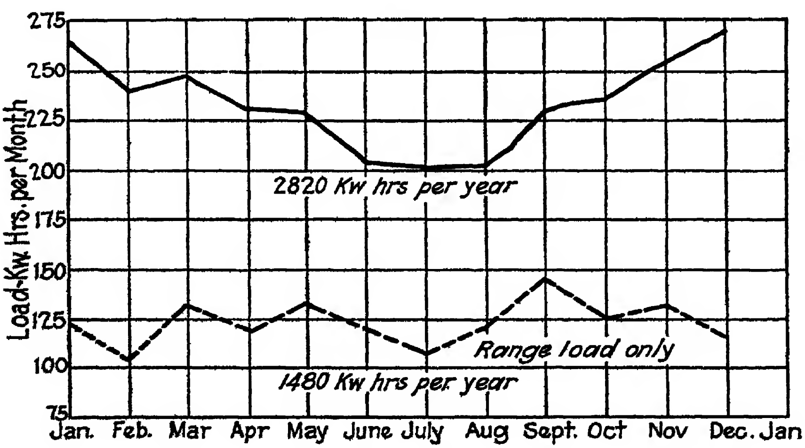

FIG. 27.—Typical yearly load—average residence customer with lighting, range, refrigerator, and oil burner.

considered only in their relative values and not as actual annual load factors since it is understood that the daily load curves of Figs. 23 and 24 were not for peak days but were merely characteristic. Actual annual load factor should be more of the order of

25 per cent. In the report of the National Electric Light Association Domestic Range Committee, the figures below are given as the result of their tests, *i.e.*.

	City	Rural
Annual load factor—light and appliances	17 65	3 05
Range	18 9	18 9
Both with water heater	19 35	21 4

The *power factor* for residence load is very close to unity except as affected by such motors as may be in operation. A fair average of about 95 per cent may usually be assumed for a group load, including the effect of inductance in secondary lines, etc.

It is often convenient to consider residence load as uniformly distributed along the lines although there will nearly always be a sprinkling of larger loads or loads of different character which upset the uniformity of distribution. A single range on a secondary whose load is otherwise all lighting or an apartment house in a district otherwise made up of small residences are examples of this. Such loads must be taken account of when designing the circuits. Load density for uniform distribution will depend on the type of district and the degree to which it is built up. It may vary from as low as 5 kw. per 1,000 ft. of secondary (much lower than this will usually not be considered as uniformly distributed) up to 25 or 30 kw. per 1,000 ft. for ordinary light and medium residential load. Where ranges are prevalent, the density will be more of the order of 50 kw. or more per 1,000 ft., and similar or higher densities will be found in the heavier residential districts containing apartments, etc.

Growth of load in a residence district depends upon so many factors, the amount of vacant property to be built up, character of population, general business conditions, sales effort, etc., that no general figures of any value can be given. It is the experience in most districts, even when well built up, that some growth from year to year may be expected. A carefully kept continuous record of load on distribution circuits is a valuable aid in predicting future conditions and designing the system.

Light residence load is most generally served from 115/230 volt (or similar voltage) three-wire, single-phase secondaries. Voltage regulation should be kept fairly close on account of the lamp load as discussed above under lamps, with especial attention to preventing excessive voltage dips due to motor starting currents or other large loads. A plus or minus variation of 5 per cent of normal voltage (steady voltage, not dips) should not be greatly exceeded for good conditions and for more dense city load somewhat closer regulation is justified, ordinarily.

Continuity of service to light-residence load is desirable but it may be said that absolute 100 per cent reliability is usually not an essential to the extent that a large expenditure is warranted to insure it. The degree of reliability which it is practicable to maintain will depend somewhat on the character of load and its density, *i.e.*, rural customers cannot be given as high a degree of reliability as city load with reasonable expense. Outages are always an inconvenience and if too frequent or of too long duration will reflect in the attitude of the customers toward the company. For this class of load in general they are usually more of a nuisance than a hazard.

Residence Load—Heavy.—No sharp dividing line can be drawn between light- and heavy-residence load, the characteristics of all such loads being quite similar. As was pointed out above, the load of a group which might otherwise be of fairly low density, may be fairly heavy due to a general use of electric ranges, water heaters, etc. However, very heavy residence load is usually made up partly or wholly of apartment-house load. This load, as far as the lighting and appliance load of the individual apartments is concerned, is not essentially different in characteristics from any other residence load except possibly for a somewhat lesser use of appliances and somewhat higher proportion between demand and connected load. Electric ranges in each apartment are sometimes found and these affect the demand, etc., as indicated above. Considering the apartment building as a whole, however, the characteristics of its load are affected by the fact that there is often a fair amount of motor load included, such as motors on elevators, ventilating fans, pumps, refrigerating machines, etc. Such motor load has its own typical characteristics as to load factor, power factor, etc., and these must be combined with those of the lighting and appliance load to get a picture of the composite load. While no definite rule can be

set down as to the relative size of the two types of load, since this will vary with location, type of building, use of ranges, etc, a power load of 20 to 25 per cent of the lighting load will often be found. In this case there is likely to be little diversity between the lighting and power peaks, since the power is an evening as well as a day load.

A district of any considerable size with purely residential load is not usual. More often there is a certain amount of commercial load intermingled, due to stores, small shops, etc. These affect the characteristics of the load of the district as a whole.

Commercial Load (Stores, Small Manufacturing Shops, Theaters, Markets, Etc.).—Commercial load is characteristically a combined light and power load with the lighting usually predominating but not always. The proportion in which they combine depends entirely on conditions—for example, the ordinary small store will have a few motors such as coffee or meat grinders, ventilating fans, refrigerating machines, etc., but these run intermittently and may take a very small load compared with the lighting which may include a fairly large demand for window lighting, electric signs, display lighting, etc. On the other hand, some commercial loads lean more toward the manufacturing side, as in a market district where the day power load in elevators, large refrigerating machines, ventilators, food grinders and the like may greatly overbalance the lighting load.

The diversity between individual demands for power load only is likely to be high, since the power load is usually diversified as to use. For the lighting load, however, a low diversity will usually exist since with such lighting, nearly all the connected load is likely to be used at the same time. There is not likely to be much diversity between power and lighting peak for such loads.

Power factor of the motor load is likely to be low due to the tendency toward overmotoring in such types of installations. The power factor of the load as a whole at peak load will depend on the relative proportions of power and lighting load included in the total.

Commercial load is inclined to be "spotty" rather than uniformly distributed due to the difference in size and type of business of individual customers. This must be taken into account in designing the distribution system so that the individual heavy loads are taken care of. The same is true of the necessity for

continuity of service. For certain loads such as theaters, hotels, large department stores, etc. it is extremely important that as near 100 per cent reliability as possible be provided whereas with small manufacturing shops, small stores, and the like, the need is not always so urgent, although for all such load a high degree of reliability is very desirable.

Growth of load in commercial districts has been considerable of late years and bids fair to continue for some time to come on account of the growing interest and appreciation of good lighting as a sales medium.

The heaviest commercial districts in some of the larger cities are still carried on direct current. Elsewhere, the supply of alternating current at 115/230 volts for lighting and 230 volts, three- or two-phase for power is quite well standardized. The comparatively recent development of alternating current, low-voltage, multiple-feed networks has offered a possible solution to the problem of service reliability. In connection with these networks, several companies have established combined single-phase, three-phase secondary systems using either 115/199 volts or 120/208 volts. This question is discussed in some detail in Chap. VII.

Commercial loads are usually of fairly heavy density, *i e.*, running from say 25 to 50 kw. per 1,000 ft. up to very large figures in the downtown districts of cities like Chicago or New York. The character of the load, especially in the downtown districts usually demands a closer voltage regulation than is necessary in outlying districts.

Street-lighting Load.—Street lighting is a desirable type of load for the power company both on account of its favorable characteristics from the engineering point of view and also due to its advertising value.

It is a load of 100 per cent demand factor and high load factor—of the order of 50 per cent where all-night lighting prevails.

For series-type lamps, the load per lamp and power factor depend somewhat on the degree to which the series-circuit transformers, used to suply them, are loaded as well as the size of the lamps themselves. The following data are given in the National Electric Light Association Overhead System Reference Book:

TABLE II.—APPROXIMATE TRANSFORMER CAPACITY TAKEN BY SERIES LAMPS

	Lumens	Kilowatts
Individual series type.	600	0.048
	800	0.0585
	1,000	0.072
	2,500	0.16
	4,000	0.257
	6,000	0.38
Compensator type	4,000	0.3
	6,000	0.42
	10,000	0.667
	15,000	1.0

POWER FACTORS OF STREET-LIGHTING TRANSFORMERS

Indoor 91.25 to 92.5 per cent at 100 per cent load
54.5 to 57 per cent at 50 per cent load
Outdoor 75 per cent . . . . . . at 100 per cent load
38 per cent . . . . . . at 50 per cent load
21 per cent . . . . at 25 per cent load

Power Load (Manufacturing).—There is no definite dividing line between what may be called power loads and the commercial loads discussed above. The latter may be thought of, however, as loads where the lighting is of prime importance and the power more or less incidental or at least not much greater than the lighting, whereas power loads are conceived of as being predominately power with only a comparatively small amount of lighting (manufacturing plants, etc.)

Power loads usually consist to a large extent of induction-motor load. In certain types of plants, the industrial heating load plays an important part. The characteristics of the load as a whole are affected by the proportion in which the different types of load occur. They are also governed by differences in type of manufacture, method of operation, plant design, efficiency of management, and numerous other factors so that there is quite a wide variation in such elements as power factor, load factor, diversity, etc. not only between different industries but also between different individuals in the same industry. Such figures as can be given in this regard must be considered as only very general and not applicable with any degree of accuracy to any particular case without further local investigation.

Demand factor is likely to be comparatively low for power loads consisting of a large number of comparatively small units (motors and heating devices) due to the high diversity between peak loads on such units. Where the units are fewer and hence larger in comparison with the total load, the demand factor will be higher. Especially where furnaces or ovens comprise a fairly large proportion of the load, the demand factor will be high. Table III gives some characteristic demand factors for various industries found in a quite extensive survey of power loads in Detroit:

TABLE III.—DEMAND FACTORS FOR VARIOUS TYPES OF MANUFACTURING PLANTS

	Maximum Demand ÷ Total Connected Load
Asphalt	0.70
Automobile assembly	0.68
Bakery	0.54
Bedding	0.66
Boat	0.51
Body (auto)	0.68
Bottling	0.52
Brass	0.80
Brick	0.70
Cement	0.65
Cement and asbestos products	0.63
Chemists	0.50
Cleaners and dyers	0.68
Coffee	0.42
Clothing	0.45
Crane	0.80
Creamery	0.77
Drop forge	0.75
Egg provision	0.60
Electrical	0.75
Excelsior	0.90
Foundry	0.63
Garage	0.53
Gas	0.60
Grain elevator	0.69
Graphite	0.81
Hat	0.50
Ice	0.92
Ink	0.80
Knitting mills	0.86
Laundry	0.82
Lime products	0.65
Lumber	0.64

TABLE III.—DEMAND FACTORS FOR VARIOUS TYPES OF MANUFACTURING PLANTS.—(*Continued*)

	Maximum Demand, ÷ Total Connected Load
Machine shop	0.75
Meat market	0.78
Meat packing	0.79
Motor (marine)	0.82
Oil	0.60
Oxygen	0.70
Paint and color works	0.72
Paper	0.75
Paper products	0.47
Pin	0.65
Plaster	0.95
Plate glass	0.75
Pottery	0.60
Printing	0.50
Railroad (round house)	0.92
Refrigerator (iceless)	0.75
Roofing	0.60
Salt	0.75
School	0.60
Scrap metal	0.42
Sewer contractor	0.65
Sheet metal	0.44
Screw machine	0.71
Stamping	0.73
Steel	0.58
Stone cast	0.48
Stone cut	0.73
Stove	0.69
Sugar	0.75
Telephone	0.95
Tobacco	0.61
Varnish	0.75
Wire	0.65
Woodworking	0.55
Zinc process	0.55

The above table gives an average demand factor for different classes of business which it was considered could be used safely without overloading the transformer more than 25 per cent. If we wish to get more accurate demand factors, the following must be considered:

A. Total connected load—as the total connected load increases the demand factor decreases.

B. Size of individual motors, etc The larger the motors compared with total load, the higher the demand factor.

C. Grouping of motors, *i.e.*, whether customer has all large or all small motors, or a number of each.

D Ratio of size of large motors to small motors. The larger the ratio of the average of large motors to the average of small motors included in any load, the higher the demand factor.

Diversity between different power customers, especially those in different lines of business is likely to be quite high. Advantage can often be taken of this in grouping several power customers on the same transformer installation, the transformer capacity necessary for the group being perhaps no more than one-half the total necessary to serve each one separately.

Power factor of industrial power load is likely to be quite low unless special measures are taken to increase it, such as differential rates based on power factor. The general use of induction motors whose power factor at best is of the order of 80 to 85 per cent, with a quite universal and natural tendency toward overmotoring, leads to power factors of the order of 70 per cent quite commonly and in many cases as low as 60 per cent or even less. Low power factor has a serious affect on the design and costs of a distribution system. The capacities of lines, transformers, regulators, etc. are based on current carried and losses are proportional to the square of the current. Hence, since the current increases in inverse proportion to the power factor for a given effective load in kilowatts, it is evident that the distribution costs are correspondingly increased. The problem of providing good voltage regulation also is likely to become difficult. Where a considerable amount of unity power factor load is included, such as that taken by ovens, the resulting power factor of the load as a whole is higher. Low power factor may be economically raised to a reasonable value in some cases by the addition of static or synchronous condensers or the use of a certain amount of synchronous motor capacity operated at leading power factor.

Load factor for power loads, *i.e.*, large loads or groups is usually high due to long hours of daily use and small seasonal variation compared with lighting load. Figure 28 is a yearly load curve for power found on one system.

The growth of power load in any particular locality is very hard to foretell. It usually occurs in fairly large jumps due to the addition of new customers or material increase in capacity by old

customers rather than gradually. The load drawn by power customers reflects to considerable extent general business conditions, somewhat more so than commercial or residence load.

Power is quite commonly supplied at 230 volts, three-phase, although in some places two-phase is still used, especially for small power loads. For larger customers, 440 volts is also quite often used. Large customers are sometimes supplied at primary voltage (2,300, 4,000, 4,800, 6,600 volts, etc.) and sometimes, in the case of extremely large loads, the supply may be economically given at voltages in the transmission class.

Close voltage regulation for power loads is not so essential as for lighting unless the lighting combined with the power is such as to

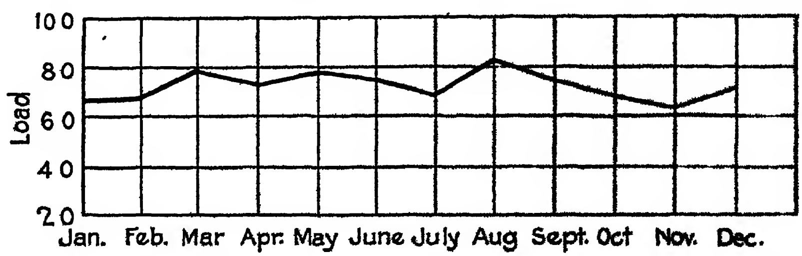

Fig. 28.—Typical yearly power load on system.

demand it or unless particular types of apparatus used require close limits. Motors are generally guaranteed for satisfactory operation at 10 per cent plus or minus rated voltage so, although such a range is not recommended, a wider range than is usual for lighting is justified. For this reason it is sometimes advantageous to carry major power load on feeders entirely separate from characteristic lighting load.

Farm Load.—Rural electrification has been increasing very rapidly of late. Along with the development of facilities for giving the farmer electric service has gone the stimulation of the use of the service by the farmer—his education as to the possibilities of greater use of electric power in farm operation. The well-equipped farmer may have an electric range and the other usual appliances in his house, water system, feed grinder, hay hoist, milker, general service motor, etc. In some localities the irrigation pump load is a primary factor. The use of electricity by the farmer is in such a stage of development at present that a definite estimate of what the average load may be is impossible.

For lines where the service is used largely for lighting, the group demand will probably be not over 150 to 200 watts per customer. Where electric ranges are the rule, an average of 1 kw. per customer may be expected (following the rules given above for range load). Other appliance and motor load may increase this demand considerably but the diversity in use of such equipment is high. Also it will be a rare case where every customer will be fully equipped Probably an average of 3 kw. per customer would be found on some of the higher class districts but more than that would be experienced only in special cases. Naturally, there will be such special cases in various parts of the country and with special types of customers (such as irrigation districts). The demand of the individual customer, of course, will depend on his equipment. The ordinary small farm equipped with a range and a fair amount of motors will probably have a demand of the order of 5 kw. Larger farms with more and special equipment may run considerably higher.

System Load.—The load on any system as a whole or a large section of it, such as that fed by a large substation, is, of course, made up of the sum of all the different types of loads carried, which are discussed above. In the larger cities, the power load generally predominates and creates the average daily peak at either mid-morning or mid-afternoon. The yearly peak usually is due to an unusual combination of lighting and power on a dark day in winter. There is sufficient diversity between the various component parts of the load, however, so that the yearly peak is rarely equal to the sum of the peaks for lighting, power, street railway, etc. separately. Figures for diversity between lines out of a substation and between loads on substations are more or less indeterminate depending on local conditions. The following may be considered as characteristic but not necessarily typical:

Between lines of similar characteristics (lighting, power, combined, etc.)	1 15
Between lines of different characteristics (general diversified load)	1.5 to 3
Between substations (general diversified load)	1 1

Figures 29 and 30 illustrate typical diversification of load on two types of substations.

System load factor on a diversified system will usually be high, depending, of course, on the amount of diversification and rela-

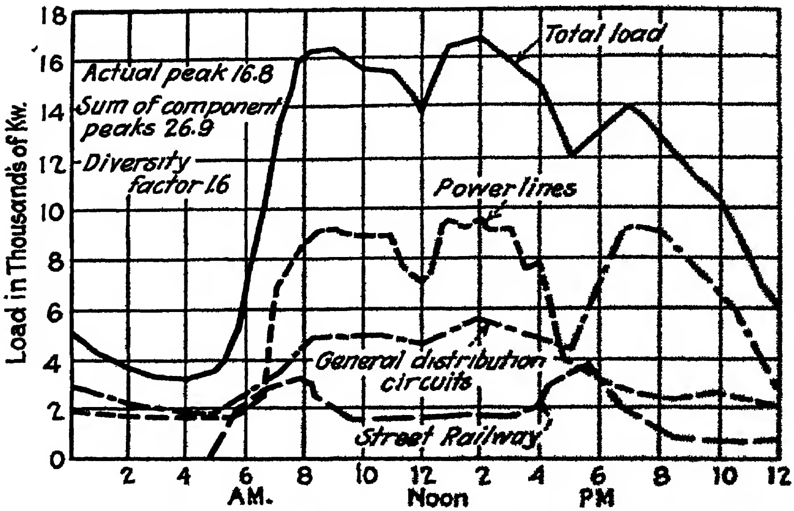

FIG. 29.—Typical actual diversified load on a city substation. Fairly large proportion of lighting load.

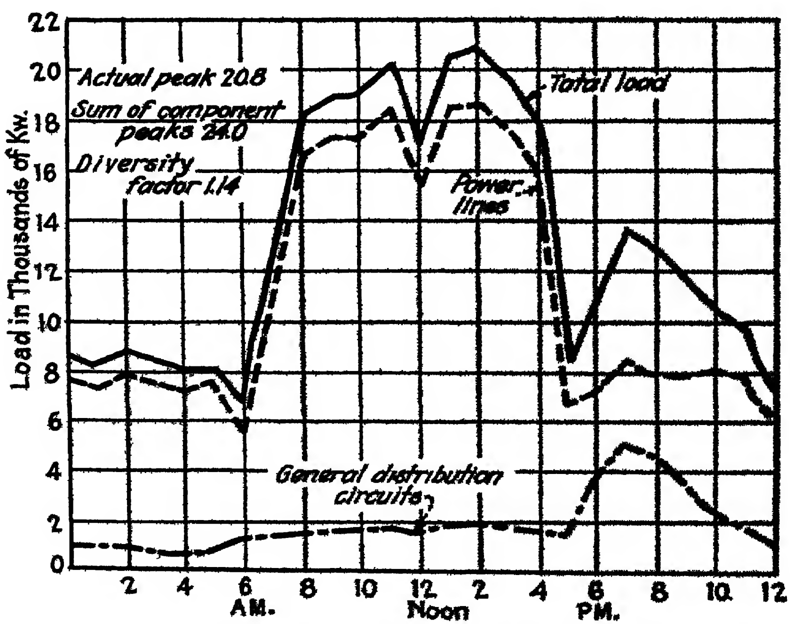

FIG. 30.—Typical actual load on a city substation; largely power load.

tive sizes of various loads. Figure 31 shows a yearly load curve from such a system, indicating relatively small seasonal variation. The load factor on such a system may be of the order of 75 per cent daily and 55 per cent yearly (30-min. maximum).

The growth of system load is a study in itself and one which is of great benefit, indeed practically essential in the making of

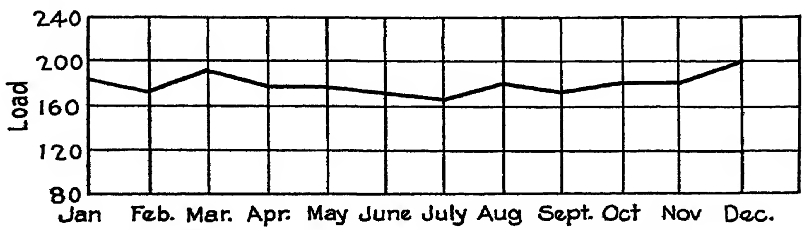

FIG 31.—Typical yearly total load on system.

future plans for the distribution system. This system should be projected, in its main features at least, 4 or 5 years in advance and this can only be done intelligently by a study of the probable future load. Such a study must include past tendencies (a continuous load curve for total load, power load, lighting load, etc., is helpful) general business conditions, records of employment of men in the industries, building statistics, and also a liberal but not uncontrolled use of the imagination

CHAPTER V

TYPES OF DISTRIBUTION SYSTEMS

There are several different ways in which distribution systems may be classified according to certain outstanding characteristics. They may, for example, be grouped according to frequency, or number of phases (if alternating current), or voltage, or general schemes of arrangement of lines whether overhead or underground, urban or rural, etc.

In some of these classifications, such as overhead and underground, or rural and urban, the different types correspond more or less to the different types of load served and examples of several or all of these types will naturally be found on the same system in many cases, especially on the larger systems. Other classifications, such as by frequency, voltage, etc., apply more to the distribution system as a whole, and, as a general rule, the fewer different types, according to any such classification, found on any one system, the better.

The most important of these classifications will be taken up and the characteristics, advantages, and disadvantages of the chief types included in each will be discussed.

Direct or Alternating Current.—*Direct Current.*—The first form in which electric current was used practicably for electric lighting and power was as *direct current*. For this reason, in nearly all of the larger cities of this country such as New York, Philadelphia, Chicago, Detroit, Cleveland, Brooklyn, etc. there will be found at least a nucleus of direct-current distribution. This usually occurs in the central downtown section where an electrical distribution system was first introduced and where the load is now heavily concentrated. Also in such areas a high degree of service reliability is usually demanded.

Variable speed control is, as a rule, more easily obtainable with direct-current motors than with alternating current and this is an important requirement for certain loads such as elevators, printing presses, etc. This has been one large contributing factor to the demand for the retention of direct-current distribu-

tion in districts where it was already installed even though the area thus served were not to be extended. Alternating-current equipment for such purposes, however, has now been developed to such a point that there is not the necessity for direct current that there was formerly.

The chief advantage of a direct-current system as a system of electrical distribution has probably been in the possibility of maintaining continuous service on it under adverse conditions which would have caused an interruption to the ordinary alternating-current system, such as the failure of a feeder or a substation or even of a generating plant for a short period of time. This has been accomplished by the use of a network system of lines and by the location of storage-battery reserve at certain strategic points on the network. The network system provided against interruption of service due to the failure of any one or even several feeders. The storage-battery reserve carried the load for a certain time even in case of the total failure of a substation or of a generating plant, enabling normal service to be quickly restored in nearly any case excepting the failure of all or a major portion of the total system of power supply.

The use of storage batteries also has the further advantage that sharp load peaks of short duration can be carried by them without throwing this additional demand on the generating equipment.

The chief disadvantages of direct-current distribution are its relative inflexibility and its higher cost. Where the power is generated as alternating current, which is the case in all systems of any considerable size, the direct-current load must be served by converting the alternating-current power to direct current by rotating machinery and distributing it at low voltage, 240 volts, ordinarily. Additional loads of any size necessitate an increase in this rotating machinery, the substation space to accommodate it, and the low-voltage feeders. These increases as a rule require considerably more work and expense than the increase necessary in an alternating-current system for a similar load increase. Hence the relative inflexibility.

As to the relative cost of direct-current and alternating-current service for the same load, authorities disagree, and it no doubt depends entirely on the governing conditions. There is probably not much question that the alternating current would be cheaper if the element of service reliability could be ignored. For serving

a load largely residential and largely overhead, where the continuity of service rendered by the direct-current network with storage-battery reserve is not so essential as it is for some other types of load, it has been figured that the direct current costs from 25 to 30 per cent more than the alternating current. This is due to the larger investment in substations, rotating machinery, etc. and the energy losses in conversion and low-voltage distribution to the network, the alternating current system enabling transformers to be located near the load and to be served at higher voltage.

Where a high degree of reliability of service is required, however, something more than the ordinary radial alternating-current system becomes necessary to enable a comparison to be made with direct current on the basis of equivalent service. The alternating-current multiple-feed low-voltage networks, with automatic protection on each transformer, appear to offer a solution to the problem of providing an alternating-current system of distribution with a high degree of reliability for serving a large group of customers or a district. There is still no equivalent to the direct-current, storage-battery reserve, but on a large system with several sources of main supply all of which are not likely to fail at the same time, it seems probable that the alternating-current network, will give a satisfactory degree of assurance of service continuity in most cases. As to the cost of the alternating-current network, comparative studies made by several authorities indicate that even with the special provisions necessary for maintaining continuous service, the alternating-current system, if properly designed, has the advantage in cost over the direct-current in addition to its advantage in flexibility. The design of these networks will be taken up in Chap. VII.

It should not be inferred from the above that it is always an economical proposition to change over an old established direct-current system to alternating-current operation. In making such a changeover, there are several difficulties and costs to be encountered which may offset all the advantage gained. The distribution lines must be more or less rebuilt, primary feeders and mains installed, and transformer locations built. In addition, the customers' direct-current motors and other equipment must be replaced with alternating-current motors and equipment. Where there is power load, the customers' wiring must be revised to separate the power and light circuits, if polyphase power is

used. One of the largest costs of such a changeover has been found to be due to apparatus and equipment of a special nature which have to be replaced by other similar special equipment instead of by standard apparatus. Added to all this, the operation of actually cutting over the system from one kind of service to the other without involving interruptions of undue length, is likely to be quite a problem. These difficulties are not insurmountable but are things which must be reckoned with in considering such a cutover. On the other hand, there are some advantages gained besides the introduction of a more flexible system, which can be more easily adapted to future load increase. Usually, there is possible the salvaging of a considerable amount of substation space and equipment, large cables and duct space in underground conduits (which may or may not be useful on the alternating-current system). It is probable that in most cases a direct-current system which is adequate for the load carried and for a reasonable amount of increase cannot be changed over to alternating current with any great amount of economy, if any. For a system which is overloaded, however, and requires immediate additions in substation and feeder capacity, there very often will be a real saving in making this change, even with the considerable expense involved as indicated above. A careful survey of any particular situation for which such a change is proposed should be made, including a detailed investigation of the customer's equipment, and wiring changes involved.

In some cases a changeover from direct current to alternating current has been made gradually, the alternating-current system being built in, paralleling the direct current, to carry new load, increases in load, and such transfers as can be readily made. This is a much cheaper method of accomplishing the result, as the direct-current load gradually drops off without a large expense for changes in equipment. It involves a considerable amount of confusion, however, in having two different types of service in the same area.

Alternating Current.—By far the greater amount of electric power used in this country is generated and distributed as alternating current. This is due largely to the fact that it can be generated at a comparatively low voltage, which can then be stepped up by a transformer (which is an extremely efficient machine) to a high voltage and the power transmitted over long

distances, if desired, with comparatively small currents and hence small losses. The voltage can then be stepped down by a transformer to an intermediate voltage for distribution and finally stepped down by more transformers to a utilization voltage at or near the point of utilization. Such voltage transformations with direct current would be very cumbersome, if possible at all, with the present-day apparatus available, and without them the long-distance transmission and distribution is out of the question. Direct-current transmission at high voltage and distribution at intermediate voltage, similar to the alternating-current systems now in use, would have marked advantages on account of the elimination of voltage drop due to inductive reactance, but at present no simple device like the transformer is available for use on direct current. Whether the developments in vacuum tubes and other devices will eventually produce such a device for general practical use remains to be seen.

Frequency.—The frequency most generally used in this country is 60 cycles, *i.e.*, the voltage, and hence the current, passes through a complete cycle from 0 to maximum in one direction to 0 to maximum in the other direction, to 0, 60 times in 1 sec. Sixty-cycle current is well adapted for use in lighting since the alternations are frequent enough so that no flicker is apparent to the eye with the ordinary lamps in use. It is also well adapted for motors. Probably the greater majority of power companies use the one frequency, 60 cycles, for both lighting and power service.

The other frequency most often encountered is 25 cycles. This frequency is also used for lighting in some places, but is slow enough so that there is a quite perceptible flicker. Those using it constantly become accustomed to this but it is very noticeable to one who is used to 60-cycle illumination. The use of 25 cycles has certain advantages in transmission and distribution in that the inductive reactance is less, being proportional to the frequency, and the motors used are inherently of lower speed. Some companies make quite general use of 25 cycles for power loads and for transmission, even where 60 cycles is used for lighting, employing frequency changers where it is necessary to change from one frequency to the other.

Other frequencies will be found here and there but they may be considered as exceptional; the 60 and 25 cycles being quite generally accepted standards. Foreign practice differs in that 50 cycles is the standard rather than 60.

Phase Relations.—With the introduction of alternating current there came the possibility of combining two or more circuits, similar except as to phase relations, *i e*, with a time differential between similar points in their voltage and current cycles, into one composite polyphase circuit, with a resultant decrease in total current and hence in losses and voltage drop.

Single-phase Circuits.—The single-phase circuit is similar to the direct-current circuit in nearly all respects except the alternation of voltage and current flow. This is the oldest form of alternating-current circuit and is used almost universally for lighting, small and medium-sized heating devices, and small motors (1 hp. and less) Hence, on any distribution system, the final step before reaching the point of utilization, for all but polyphase power loads, is a single-phase system, usually of the order of 115 volts. Two or more such circuits are nearly always combined into a 230-volt, single-phase circuit at or very near the point of utilization, and this, in turn, is usually combined into a polyphase system, sometimes in the service itself, sometimes on the secondary, sometimes in the primary feeder, and sometimes even back as far as the substation. In other words, due to its economy, polyphase transmission of energy is almost universally used as far as the substation and, in the majority of cases, at least as far as the primary feeder centers. In some cases, single-phase feeders out of the substation have been used, but in most such cases, cutover to the three-phase feeder system has been or is being made. Beyond the feeder center, single-phase primary branches for residence load are usual, but in some cases, especially where the load is a combination of power and lighting, polyphase distribution up to the customer has been used to good effect. This will be further discussed under the subject of combined light and power secondaries, Chap. VII. For distinctively power loads, of course, polyphase distribution up to the load is most often used.

Two-phase Circuits.—The combination of two single-phase circuits at a 90-deg. phase relation into one two-phase circuit effects some economy and has been used to some extent. Its use has been far outdistanced by the three-phase, however, and is now largely confined to those systems or portions of systems where it grew to considerable magnitude before the three-phase became so universally popular. Transformation from three-phase to two-phase is a fairly simple and economical matter and there is probably little or no advantage in changing over an estab-

lished two-phase distribution system to three-phase. Where only small amounts of two-phase loads are found in large, three-phase systems it may be economical, as a matter of standardization, to change them over and this has often been done. On the other hand, in at least two large cities, the two-phase secondary system is being extended, especially for secondary networks, as

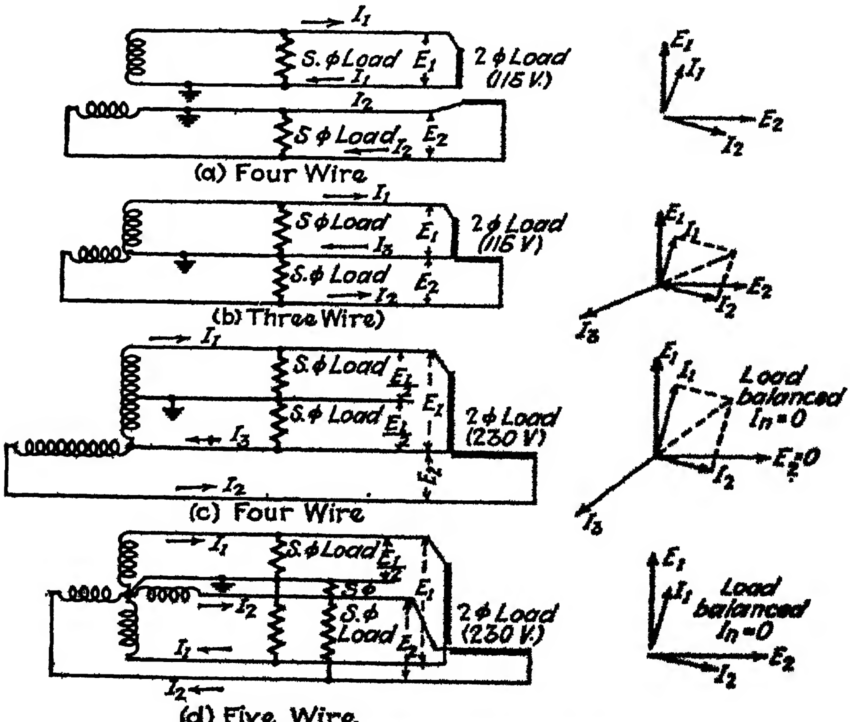

FIG. 32.—Two-phase circuits (secondary).

it shows some marked advantage when used with a combined light and power system. Even in these cases, however, three-phase is used for transmission and primary distribution.

Two-phase distribution circuits appear in several different forms. The four-wire circuit is essentially a group of two separate, two-wire, single-phase circuits whose voltages are 90 deg. out of phase with each other, Fig. 32(a). These circuits, if used for secondaries, will usually have a voltage between wires of the order of 115 volts (with one side grounded as a rule), carrying single-phase loads on both circuits and 115-volt polyphase loads by a combination of the two. They are probably more

often used in this way for wiring within a service than for distribution.

If one side of one of these two-wire circuits is connected to one side of the other, the currents in the two wires thus tied together will combine, and since they are 90 deg. out of phase with each other, the resultant current will be $\sqrt{2}$ times the former current in either. One of these wires may then be omitted, thus forming a three-wire, two-phase circuit, Fig. 32(*b*), in which one wire carries 1.41 times as much current as the other two. This common phase is ordinarily grounded for secondaries. The voltage between it and each of the other wires is of the order of 115, while that between the other wires themselves is 1.41 times as much. This three-wire circuit is the one most commonly used for two-phase primaries.

Another four-wire circuit may be obtained as shown in Fig. 32(*c*). In this case, one side forms a three-wire, single-phase circuit, with the middle wire grounded, carrying the single-phase load. A "teaser" wire is run for the other phase (at 230 volts) to carry polyphase loads.

The five-wire circuit shown in Fig. 32(*d*) consists essentially of two three-wire, single-phase circuits with the middle wires tied together and combined into one wire and grounded. Single-phase loads are connected between the grounded wire and any of the other four-phase wires at 115 volts. Two hundred thirty-volt two-phase motors are connected to the four outside wires This is the most efficient of all the two-phase circuits and is the one used for heavy, general-purpose secondarys, such as alternating-current secondary networks, where two-phase is employed. It has also been used to some extent for primary feeders, but for this purpose has the drawback of tying up a considerable amount of load on one circuit.

Three-phase Circuits.—Three-phase circuits are the most commonly used of all for transmission and primary distribution and also for secondary distribution to power loads. Essentially, a three-phase circuit may be thought of as consisting of three single-phase circuits whose voltages are 120 deg. out of phase with each other. If one side of each of these three circuits (assuming them to be equally balanced) is tied in to a common conductor, the resultant current in that conductor, being the sum of the three component currents, will be 0. Hence the common conductor may be omitted.

The three-wire, three-phase circuit thus formed, Fig. 33, is the one commonly used for transmission and for secondary distribution to three-phase motors and quite largely for primary distribution also. Single-phase loads are connected between two-phase wires. Three-phase loads may be similarly connected

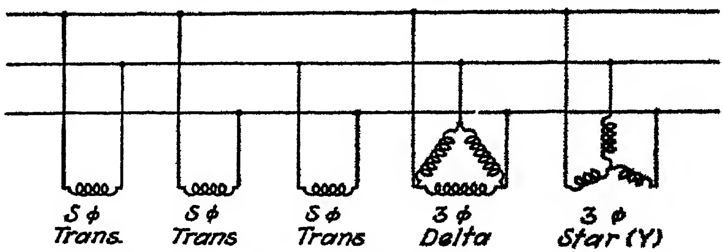

FIG. 33.—Three-phase circuit, three-wire primary.

(in delta) or may be connected from phase wires to a common neutral point (star or Y). It is preferable to have the load on the three-phase circuit balanced as nearly as possible, but unbalanced load may be carried with, of course, an attendant unbalancing of voltage.

A four-wire circuit based on the three-wire or delta system is sometimes used for secondaries to serve combined three-phase

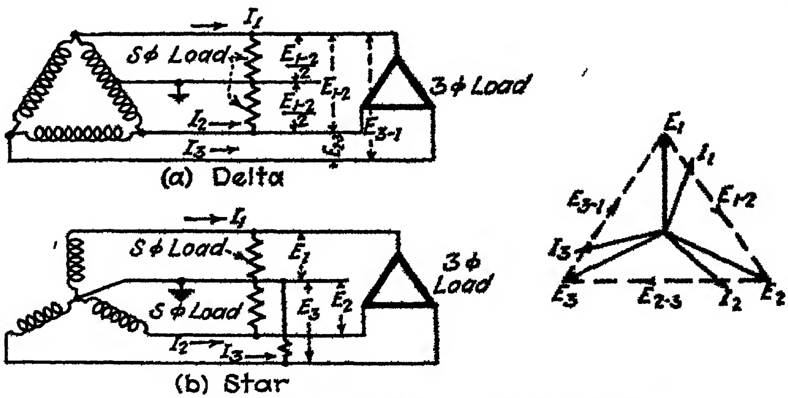

FIG. 34.—Three-phase circuit; four-wire (secondary).

and single-phase load Fig. 34(a). The fourth wire is brought out from the middle point of one of the phases and grounded. All the single-phase load is connected on this phase, the three-phase load being connected as usual in delta on all three phases. This circuit will be discussed further in Chap. VII under "Combined Secondaries."

The four-wire, Y-connected system, Fig 34(*b*), is quite commonly used for primary circuits and also for combined secondaries. It consists of the combination of the three-single-phase circuits described in the first paragraph of this section, with the common or neutral conductor retained. When the load is not equally balanced among the three component circuits, the neutral conductor will carry current, *i.e.*, the vector sum of the three-phase currents. In this system, the voltage between phase wires is $\sqrt{3}$ times that from phase to neutral. Single-phase load is usually connected between phase wire and neutral; single-phase branches from a four-wire, three-phase feeder are also usually so connected, since the phase to neutral voltage as a rule corresponds to a standard single-phase transformer voltage (2,300 volts is the most commonly used). Single-phase load or branches could be connected between phase wires at the higher voltage but this not usual on account of the odd voltage (if phase to neutral is standard). If this practise is desired, the neutral wire is of no use and the three-wire circuit is the more advantageous. Three-phase loads on primary circuits are generally connected in Y (phase to neutral). Where the system is used for secondaries, however, motor loads are connected in delta or between phase wires. The odd ratio between the phase-to-neutral and phase-to-phase voltages ($\sqrt{3}$) requires a non-standard (at present) voltage to be used for one or the other, or both. This gives rise to certain complications which are discussed further in Chap VII under "Combined Secondaries."

For primary four-wire circuits the 2,300/4,000-volt combination is most often employed. This is taken up in some detail in Chap. VI. 4,600/8,000 volts and 6,600/11,400 volts have also been used to some extent.

COMPARISON BETWEEN VARIOUS TYPES OF SYSTEMS CLASSIFIED AS TO PHASE RELATIONS

Table IV gives a comparison on a ratio basis between the various types of systems commonly used. The comparison between amounts of copper used are based on the assumption of the same size of conductor in each case. This must be considered in connection with the corresponding line loss as indicated in the figures for loss ratio and copper ratio. The latter gives the best basis of comparison, since copper sizes may be varied for the different

TABLE IV.—COMPARISON BETWEEN VARIOUS TYPES OF SYSTEMS CLASSIFIED AS TO PHASE RELATIONS

Assuming the Same Total Load in Each Case, Balanced between Phases on Polyphase Systems

	Direct-current		Single-phase		Alternating-current two-phase			Three-phase	
	Two-wire	Three-wire	Two-wire	Three-wire	Three-wire	Four-wire	Five-wire	Three-wire	Four-wire
Copper used:									
(a) All conductors same size	1	1½ (1.5)	1	1½ (1.5)	1½ (1.5)	2	2½ (2.5)	1½ (1.5)	2
(b) Neutral conductor one-half others	1	1¼ (1.25)	1	1¼ (1.25)	1½ (1.5)	2	2¼ (2.25)	1½ (1.5)	1¾ (1.75)
Line loss:									
(a) Voltage to neutral the same (or between wires for three-phase, three-wire)	1	¼ (0.25)	1	¼ (0.25)	½ (0.5)	½ (0.5)	⅛ (0.125)	½ (0.5)	⅙ (0.167)
(b) Voltage between wires the same (maximum)	1	1	1	1	1	1	½ (0.5)	½ (0.5)	½ (0.5)
Line voltage drop—100% power factor	Same figures as for lines loss								
Line voltage drop—other power factor	Depends on wire size and spacing								
Loss ratio × copper ratio all conductors same size:[1]									
(a) Voltage to neutral the same	1	⅜ (0.375)	1	⅜ (0.375)	¾ (0.75)	1	5/16 (0.3125)	¾ (0.75)	⅓ (0.333)
(b) Voltage between wires the same	1	1½ (1.5)	1	1½ (1.5)	1½ (1.5)	2	1¼ (1.25)	¾ (0.75)	1

[1] The quantity "loss ratio × copper ratio" offers the best comparison between the various systems as it includes both of these variable elements which are more or less inversely proportional to each other. It gives the ratio of copper used in case the line loss is the same for each case or the ratio of loss in case the same amount of copper is used in each case

types with corresponding changes in losses, but the relative value of the product of loss ratio and copper ratio remains the same.

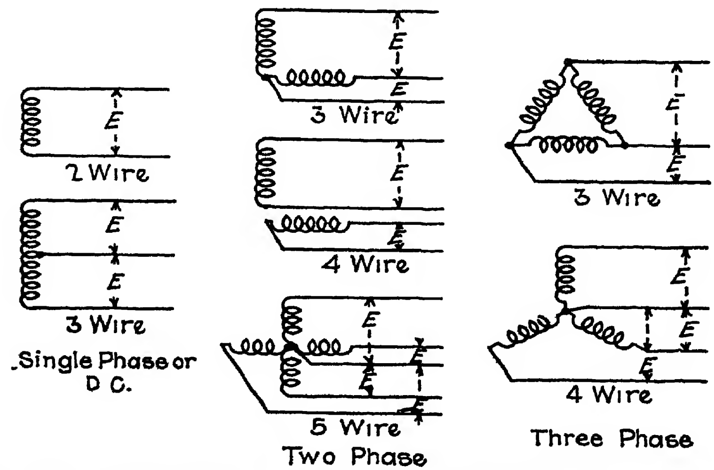

FIG. 35*a*.—Accompanying Table IV. Voltage to neutral the same.

The comparison between line loss is made on two different bases (*a*) with the voltage to neutral the same in each case (except for

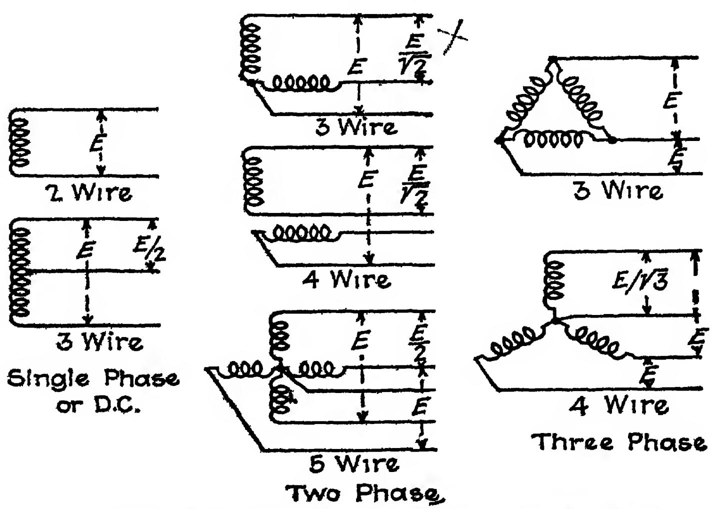

FIG. 35*b*.—Accompanying Table IV. Maximum voltage between wires the same.

three-phase, three-wire, for which the voltage between phases is assumed the same as that from phase to neutral in the other types). Figure 35(*a*) illustrates the comparison.

(*b*) With the maximum voltage between wires the same in each case, Fig. 35(*b*).

In using these comparisons, the conditions must be thoroughly understood. For three-wire, single-phase, the voltage between outside wires is twice the voltage to neutral while for two-phase, three-wire, the voltage between outside wires is only 1.41 times the voltage to neutral; for three-phase, four-wire, 1.73 times, etc. Hence, if these are compared on the basis of the same voltage to neutral, the single-phase, three-wire has somewhat the advantage. It may often happen that the maximum voltage between wires is a limiting factor, in which case the basis of comparison given in (*b*), *i.e.*, with maximum voltage between wires the same, is more representative. This shows a marked advantage for three-phase, three-wire.

For a numerical example, assuming 2,300 volts to neutral, the corresponding circuit voltages under (*a*) would be

	Volts
Single-phase, three-wire	4,600
Two-phase, three-wire	2,300
Two-phase, five-wire	4,600 (between outsides)
Three-phase, three-wire	2,300 (between phases)
Three-phase, four-wire	4,000 (between phases)

This is somewhat unfair to the three-wire, three-phase for which a voltage of 4,600 volts between phases would be more comparable. From the table it appears that under condition (*a*), the five-wire, two-phase circuits is the most advantageous while under condition (*b*), the three-phase, three-wire has the advantage over all others.

When secondaries are considered, the voltage to ground is likely to be more often the governing factor. Even here, however, a two-phase or three-phase secondary with the midpoint of one-phase grounded may be used rather than a two-phase, three-wire with the common wire grounded or a three-phase, four-wire with the neutral grounded. In such case, condition (*b*) of the table should be used rather than condition (*a*) for comparison.

It is interesting to note the comparatively small difference between the copper efficiency of single-phase, three-wire and three-phase, four-wire as used for secondary distribution (one $\frac{3}{8}$, the other $\frac{3}{9}$). When the additional pole space, insulators,

etc., for the fourth wire is considered, it is doubtful if any economy could be shown for the three-phase system for carrying single-phase load only. Its advantage of course is in being able to carry three-phase power loads as well.

Similarly, for the five-wire, two-phase system, for either primary or secondary, if smaller wire is used for carrying the same load as would be carried on a single-phase circuit, for example, the pole space, etc. may become an important factor. If more load is carried per circuit with the same size of wire, the total load per circuit may become so large as to be unwieldy as a unit in a distribution system.

The table shows very clearly the advantage of the three-wire, direct-current or single-phase, alternating-current system over a two-wire system. This is due, of course, to the fact that the circuit voltage is twice as great with only 50 per cent additional wire, even where all three wires are of the same size.

Series Circuits.—The use of series circuits is confined almost entirely to street-lighting service. Direct-current series circuits were formerly used quite extensively with arc lights but these have been largely displaced by alternating-current circuits serving incandescent lamps. The multiple or constant-voltage system for street lighting is popular in some places and seems to be coming into somewhat greater favor as effective methods of control are devised but the series circuit is still by far the more commonly used for that purpose. The constant-current series circuit is simply one in which the current is held at a constant value, passing through all the lamps in series, and is controlled by varying the voltage at the source by a variable voltage transformer. Series street-lighting circuits quite commonly carry current of the order of 6.6 amp. with voltages at the source running up to 5,000 to 7,000 volts. (See Chap. IV for further details in regard to street-lighting load, and Chap. VIII for street-lighting circuits.)

Overhead or Underground.—While not essentially different in their chief electrical characteristics, overhead and underground distribution systems are very different in actual construction and serve quite different purposes. Underground distribution for light and medium load densities is several times as expensive as overhead. Hence, it is usually impracticable to go to underground to any great extent simply as a matter of beautification of our streets as is often urged by the uninitiated. If under-

ground distribution were universally required it would hamper the development of the electrical industry to a great extent. The higher cost of serving such areas of low and medium load density would necessarily be reflected in rates and hence the growth of utilization would be hampered. Extensions into undeveloped territory would be out of the question in many cases. It is the general use of overhead lines, in spite of their comparative unsightliness, which has permitted the enormous expansion we have experienced in the electrical industry in this country.

Underground distribution, however, has its place. Where traffic conditions are very congested it is sometimes extremely difficult to build and maintain overhead pole leads, find proper locations for transformers, etc. In such cases underground distribution becomes necessary in spite of the additional cost or it may even be cheaper. Also where very dense load is encountered it may be almost impossible to carry sufficient wires on overhead poles to serve it. The number and size of conductors in underground is only limited by the number and size of ducts which may be installed, and the possible load density per 1,000 ft. of street or alley is very much higher than with overhead. One very common use for underground is in bringing out lines from substations to overhead at some distance, to relieve the congestion around the substations.

While an underground system is not subject to damage due to storm conditions, traffic, etc., on the other hand, when trouble does occur, it is much more difficult to locate and repair than on the overhead. For this reason extra provisions for maintaining service, such as throwover lines, networks, etc., are much more necessary on an underground system. Also the lesser ability for heat radiation in an underground system limits the possible load and overload which can be carried much more so than is the case with overhead.

Urban and Rural.—There is no sharp dividing line between distribution systems which might be called urban and those which might be called rural. In the vicinity of a large city, the load density, in general, tapers off more or less gradually from a very high density at the center of the city to a very low density in the outlying rural districts at some distance. In between, the load, and hence the distribution system best adapted to serve it, may pass through several variations. In general it might be said, however, that urban distribution, as such, contemplates the

carrying of fairly heavy loads at comparatively short distances, while typically rural distribution is that which carrys comparatively light loads at quite long distances. For example, a typical city residence load might be 1,000 or 1,200 kv-a. on a single feeder all in an area of 24 city blocks or ¼ square mile, with the feeder possibly not over ½ mile long. On the other hand, true rural distribution might possibly serve a load of not more than four customers per mile along a road for 10 or 15 miles with a total load of not over 25 or 30 kv-a.

In urban distribution, the factors of close voltage regulation and maintenance of continuous service without interruptions are likely to be very important ones. Also, careful consideration of the most economical arrangement of lines, conductor sizes, methods of operation, etc. are well warranted since with the heavy loads involved, a comparatively small percentage of saving in operating expense means a considerable total amount saved.

On typically rural lines, on the other hand, the chief requisite is likely to be as low first cost as can be had commensurate with satisfactory operating condition. Mechanical strength is usually of more importance as a criterion of design than electrical conductivity. The character of the load and its location usually allows somewhat more leeway in the matter of voltage regulation and allowable outages than city conditions. Higher voltage on the primary lines than would be considered good practice in congested urban territory may sometimes be allowable. Appearance of the lines is not so important and allows possibly a cheaper grade of poles to be used and less attention to grading the lines, etc. Necessary clearances above ground are usually less, making shorter poles satisfactory. As a rule, the typical rural lines will be constructed on fairly short poles, at comparatively long spans, with wire size as small as is commensurate with the necessary mechanical strength and voltage as high as may be economically used.

CHAPTER VI

PRIMARY DISTRIBUTION

The whole system for the distribution of electrical energy from the generators to the ultimate consumers may be divided, as a rule, into several quite distinct parts. While these parts are more or less interrelated and interdependent in their design, they may be more easily considered individually. Figure 36 illustrates this division of a typical system. All systems, of course, do not include all the parts shown, some omit the primary transmission, for example. Others distribute directly at generator voltage.

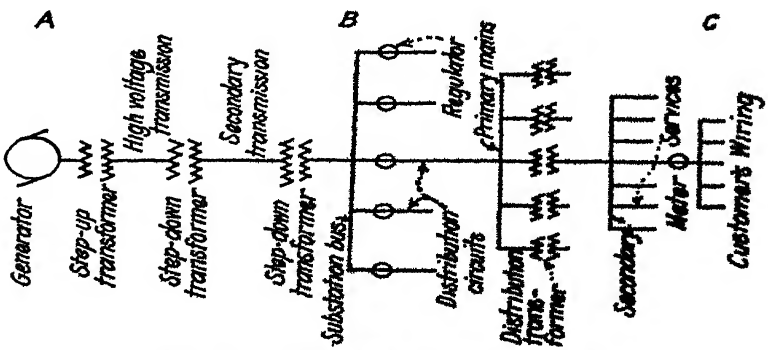

FIG. 36.—Divisions of typical system.

Also, some customers may take their service at transmission or primary voltage. In general, however, the subdivisions shown are typical of the large system.

With that part of the system from *A* to *B*, Fig. 36, we are not so directly concerned in this book, as this part lies within the province of the generating and transmission systems whereas here we are dealing more particularly with distribution from the substation to the customer. That is not to say, however, that in planning that part, the requirements of the distribution system

may be overlooked To accomplish the most efficient and economical design for the system as a whole, all of its parts must be considered not only individually, but also in their relation to other parts.

In dealing with the distribution system in its more limited sense, two rather natural subdivisions are evident. The first may be designated as *primary distribution* and includes the consideration of those lines and equipment which carry the load at higher than utilization voltage from the source (substation) to the point where the voltage is stepped down to the value at which it is utilized by the customer. The second subdivision may be called *secondary distribution,* comprising that part of the system operating at utilization voltage, up to the customer's meter. From that point to the customer's point of utilization, *i.e.*, lamps, motors, etc., the wiring system may be considered as customer's wiring and is not, as a rule, the particular concern of the power company. *Primary distribution* will be especially considered in this chapter, *secondary distribution* in the chapter following. Before going to the discussion of primary distribution as such, a few words will be said concerning the importance of the proper location of substations in its relation to the distribution system.

Substation Location.—The location of substations is a very important factor in the design of the distribution system. In general, the higher the distribution voltage, the farther apart substations may be located. Hence, where the choice of voltages is not restricted by other considerations, a study to determine the most economical voltage must include substation costs and transmission costs as well as cost of primary feeders, mains, and transformers. Where the voltage is established, a study of substation spacing and location with respect to the load concentration will often repay the effort extended, by producing substantial economies. In general, the following considerations should be met in locating a substation.

1. To locate the substation as close as practicable to the heaviest part of the load to be served or the load center, *i.e.*, so that the summation of load times distance from the substation will be a minimum.

2. To locate the substation at such a point that all prospective loads may be conveniently reached without undue voltage regulation and with the standard equipment available

3. To choose a location which will allow convenient access for incoming transmission lines and outgoing distribution lines, also anticipating a reasonable amount of growth.

4. To choose a location which will allow a reasonable amount of expansion of the substation.

5. To choose a site where property restrictions zoning laws, etc., will allow that character of building and where its erection and operation will not be a source of complaint from surrounding property holders.

6. To keep the load on the station within such limits that an undue amount of area or number of customers will not be affected by a shutdown of the station if such should occur.

7. Other general considerations such as location relative to other substations, adaptability to a general plan of distribution both present and future, facility for throwover of distribution circuits to lines from other stations in emergency, general desirability of site for a building location, etc.

Arrangement of Primary Circuits.—The type of primary feeders radiating from the substation to feed alternating-current loads will depend very largely on the arrangement and characteristics of the load carried. Since on most systems several distinct types of load will usually be found, ordinarily several types of primary feeders will therefore be used, since no one type is best adaptable to all conditions.

Trunk and Branch.—The simplest form of feeder is that which is sometimes called the "trunk-and-branch" type. It leaves the substation and runs out along a certain road or street or in a certain general direction, picking up load as it goes, by smaller branches off the main stem. It may consist of one main trunk with short lateral branches along its whole length, or there may be two or more main branches. In any case, the characteristics of this type of circuit are that the area served has usually no well-defined boundaries, and the length of the primary from the substation to its extremities is limited only by the maximum regulation at the furthest customer. The latter depends, of course, chiefly on the voltage, load, and size of wire, and is restricted to certain limits by either governmental regulation or good practice. Figure 37 illustrates such a system.

This type of primary is best adapted to scattered loads, especially small ones, and general distribution of low load density It is generally used for smaller towns and rural distribution and

in larger cities, for power lines when power loads are carried on circuits separate from those used for general distribution. Usually the size of conductor used in the main trunk is larger than that in the branches, and it may be reduced somewhat as the trunk gets farther away from the substation, on account of the smaller load carried. For a rapidly growing system, however, it is sometimes well to carry the main feeder through at a fairly good size to allow for increase in load and facilitate dividing the load later on. In fact, for such a system it is well to have in mind an eventual plan for distribution to serve the area when it is well developed and to have that plan in mind when planning all parts of the circuit. The sizes of wire to be used for this as well

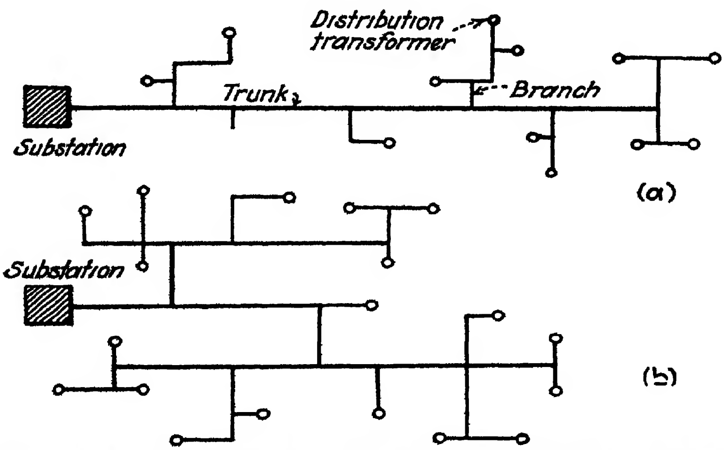

FIG. 37.—Trunk and branch system: (*a*) one trunk; (*b*) branching trunks.

as all other types of circuits should be determined by a study of voltage regulation and economy, both of which factors will be taken up in more detail later.

On polyphase feeders, balance is maintained by tapping transformers and laterals off alternate phases along the line. Laterals may be single-phase if the load carried on them is small, but should, as a rule, be changed to polyphase if any considerable proportion of the total load is carried thereon (or if polyphase service is required, of course). No definite rule can be given for this. Theoretically, the best condition is obtained by maintaining a uniform balance along the line rather than balancing in large blocks as, for example, connecting the first third of the line on one phase, the second third on the second phase, and the

last third on the third-phase. A rule for perfect balance is that the sum of the quantities obtained by multiplying each load by its distance from the source (substation) shall be the same for each phase.

$$\Sigma \text{Load} \times \text{distance (phase 1)} = \Sigma \text{load} \times \text{distance (phase 2)} = \Sigma \text{load} \times \text{distance (phase 3)}.$$

Load increases are taken up by extension of the lines until the capacity of the feeder is reached, then by subdividing it between two or more similar feeders. Eventually, if the load continues to increase, it may be necessary to run feeders out to some distance from the substation before they begin to pick up load. This, however, then begins to simulate the second class to be discussed, *i.e.*, feeder and main.

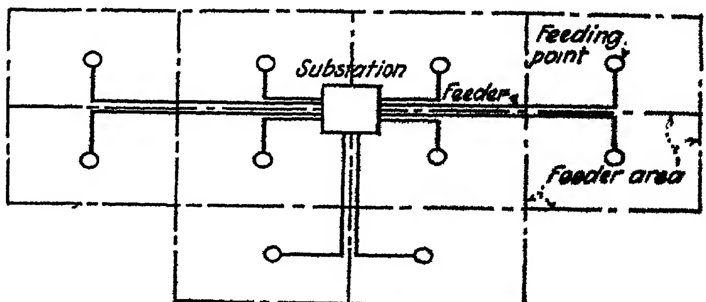

FIG. 38.—Feeder and main system (feeders only).

Feeder and Main.—Where the load served is of a fairly high density, as in the general distribution in the built-up districts of a large town or city, it is usually advantageous to divide the territory served into distinct feeder areas, with fairly definite boundaries. Each area is fed by its own feeder running from the substation direct to the area, without picking up intervening load, and there tying into the primary mains of the area. This is illustrated by Fig. 38. The size of the area depends, of course, on the load density and the capacity of the feeder and substation equipment, both as to allowable current and also as to regulation over the distance from the substation.

It is usually advantageous to choose one or two standard sizes of conductor for use on all feeders, taking into account the density of load to be served, its probable growth, length of feeders, sub-

station size and arrangement (which, of course, depends in turn considerably on feeder size), and economical operation. Care should be taken to have the standard sizes of substation switches, regulators, etc., underground cable, and overhead lines correspond so that there will not be excess unusable capacity in any section of the circuit.

Polyphase feeders are usually used on account of the greater economy of copper, the load being balanced among the phases, on the primary mains.

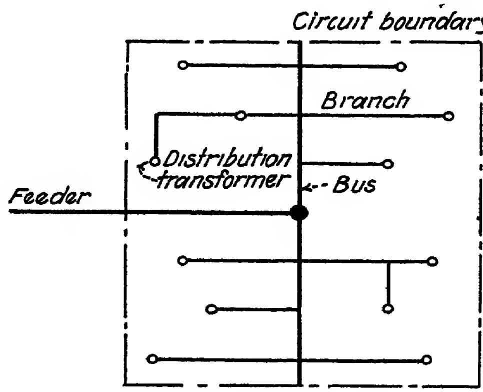

FIG. 39.—Straight bus.

In the area served, the primary mains may be laid out in any one of several various arrangements according to the topography and arrangement of load. The simplest form is that of a main bus with laterals branching to individual transformers, Fig. 39 In case the secondaries are not tied together into banks (see Chap. VII), transformers and single-phase laterals may be balanced alternately on the various phases along the bus and polyphase laterals. It is often preferable to have a primary *ring* or network instead of the single bus, if physical conditions permit. An example of this is shown in Fig. 40 for a three-phase circuit. In this case the main ring and cross-tie are three-phase, with single-phase or three-phase laterals as necessary. The area is shown divided into three phase-areas with all the single-phase load in any one area on the same phase. This is necessary if the secondaries in each area are banked. If such banks are too large, six areas may be used instead of three (or possibly five areas with one larger than the rest, etc.). If the secondaries are not banked, no phase-area division is neces-

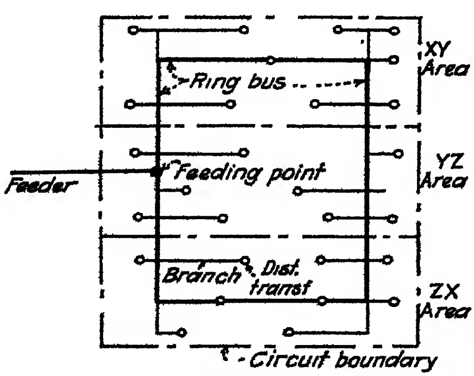

FIG. 40.—Ring bus.

sary and the load may be more easily balanced by connecting alternate transformers on different phases.

Another method of providing primary rings is shown in Fig. 41 where a main three-phase bus is used with individual single-phase rings in each phase area, a sort of combination of the ideas illustrated in Figs. 39 and 40. The advantages of using the primary ring instead of the straight bus is that, in case of a break in the main primary ring, no service may be interrupted, except perhaps for a short period, while with the straight bus, a break in that bus cuts off the service to the area beyond the break until the bus is repaired. Where secondaries are banked, the ring is also of advantage in that the primary is always live and is handled as such, whereas with the straight bus, in case of a break in the bus, the primary beyond the break might be assumed to be dead by men working on it, whereas it would in reality be kept live by feed back from the secondary.

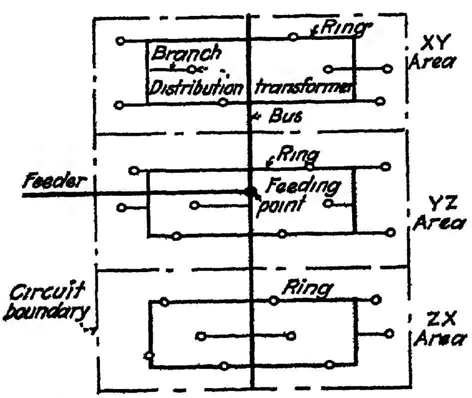

FIG. 41.—Three-phase straight bus with single-phase rings.

In any of the above cases, the main bus or the ring should ordinarily be of larger sized conductor than the laterals—for example, No. 2 or No. 0 ring with No. 6 laterals. In laying out such circuits, thought should always be given to the possibilities of revamping the system when necessary as the load increases. The original layout should be such as to care for a reasonable number of years' increase without change, but in any district where the load is growing, and in most localities such is the case, there comes a time when the feeders become overloaded and it is necessary to run additional feeders and create additional feeder areas by cutting up the old ones. From this standpoint, the straight bus layout with no phase-area division is the most satisfactory as it can be easily resubdivided as shown in Fig. 42. However, the banking of secondaries is also of advantage and that advantage may outweigh the disadvantage of comparative inflexibility. An idealized layout redividing such an area from two-feeder to three-feeder service is shown on Fig. 43. It involves the dividing

up of two of the phase areas under the two-feeder plan to three-phase areas under the three-feeder plan. Obviously, it is usually very difficult to adapt any such simple layout to field conditions to any considerable extent. The dividing and redividing of

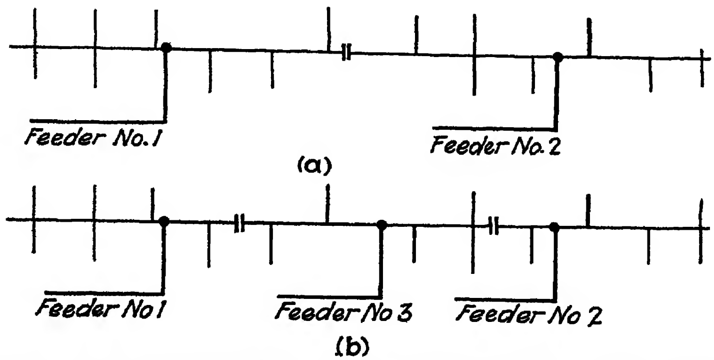

FIG. 42.—Redividing straight bus. (a) two feeders; (b) three feeders.

circuit areas is work that requires careful study of field conditions and application of a considerable amount of good judgment in laying out compact, well-defined areas, with the load well

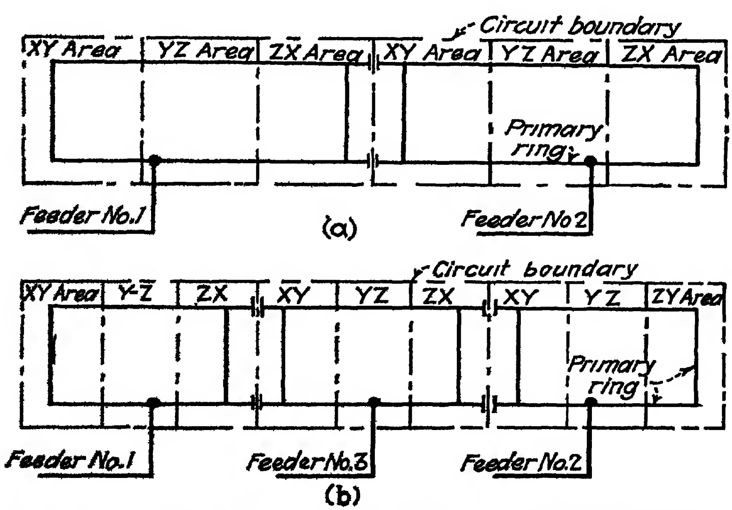

FIG. 43.—Redividing ring bus and phase-areas. (a) two feeders; (b) three feeders.

balanced and still have the design flexible for future changes. It may be said that, for the phase-area type of layout, it is usually advantageous to allow, at the time it is laid out, for a longer

period of load increase than is necessary for the system without secondary banks or phase areas.

Throwover or Emergency Connections.—Provision against interruption to service in case of trouble on primary feeders or mains is always desirable, but the necessity and practicability of making such provision depend considerably on the type of load and type of circuits. For scattered load of light density, throwover provisions, except possibly at the station end, are usually impracticable. For load of heavier density, especially where the "feeder-and-main" system is used, it is usually convenient to provide throwover points between feeders or between the primary mains of adjacent areas or both. Where the lines are all or part underground the desirability of effective emergency throwover becomes more urgent. This is not because underground lines are more subject to interruption but because, if an interruption does occur, it is much more difficult to locate the trouble and repair it than with overhead lines. Overhead lines may be rapidly patrolled and sectionalized if necessary and, if a break is found, it may require only a simple splice or the splicing in of a short section of wire to repair it. On underground, on the other hand, visual patrolling is impossible, sectionalizing is difficult if it involves cutting of cables, and splicing in a new section of cable in case of a fault is a comparatively long process. With the overhead, also, wires will often burn or fall clear in case of a break or a short circuit and although an interruption occurs, service may be restored by reclosing the circuit breaker. With underground, on the other hand, at primary voltage, a short circuit will not ordinarily burn itself clear and the circuit is down until the trouble is located and repaired.

A further advantage of having satisfactory throwover is that the feeder may be shut down for maintenance work, rearrangement of circuits, etc., without it being necessary to interrupt the service.

The degree of throwover protection required and the method of providing it are, of course, matters for consideration in connection with the type and requirements of the load and the arrangement of circuits. For certain loads such as the heavy concentrated loads in downtown districts of large cities, consisting of hotels, theaters, large department stores, etc., an interruption, even if of short duration is likely to be of serious consequence. For ordinary residence load, on the other hand, an occasional short

interruption, while inconvenient, is not likely to be dangerous For the former case, methods for *automatically* maintaining or restoring service are required and must apply not only to primary

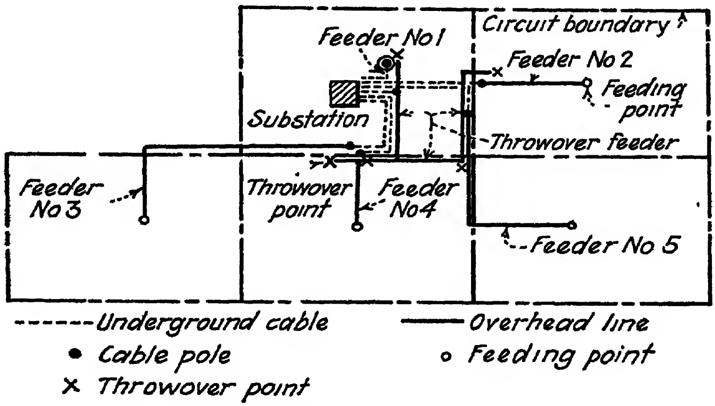

Fig 44.—Throwover—spare feeder

feeders and mains but also to transformers and secondaries. For this purpose, the direct-current networks or the alternating-current secondary network in some form are the best solutions. For the other case, where occasional short interruptions are considered allowable, it is usually sufficient to provide throwover for the feeders, especially if they are underground for part or all of their length. This may be done either by the use of a spare feeder with throwover points to several operating feeders, all of which may be normally loaded to capacity, or by using all feeders as operating feeders but allowing enough reserve capacity in each to care for a certain share of the load of any feeder which may drop out. Figure 44 shows a typical example of the first

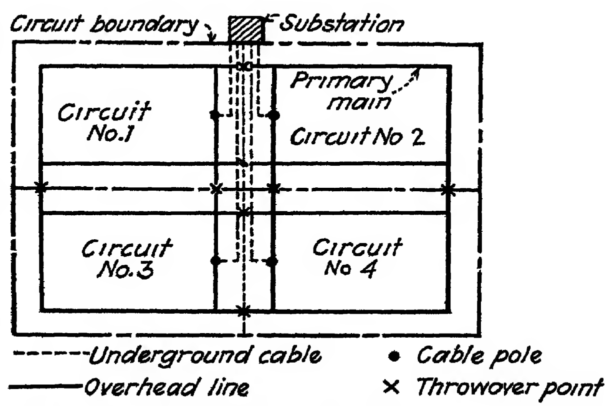

Fig. 45.—Throwover—between areas (primary mains).

type. Figure 45 shows an idealized arrangement of the second type, the primaries in each feeder area meeting and having throwover possibilities to those of two adjacent areas. In this case, if effective throwover at peak load is provided, each feeder can be loaded at peak to only two-thirds of its capacity and provision must be made for dividing the load of any faulty feeder between both the adjacent circuits. This method provides throwover for troubles on a greater proportion of the total length of feeder and mains on any circuit than does the first. A combination of the two methods is also sometimes used whereby a spare throwover feeder is provided which can assume the peak load of any faulty feeder. Throwover points between primary mains in adjacent areas are also provided and, although it would not be allowable to use these for carrying all the load of the faulty circuit at its peak, at any off-peak time they may be used, and to good advantage in many cases.

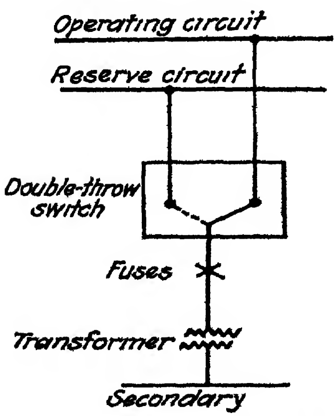

FIG. 46.—Throwover—single customer.

There are certain types of individual loads, such as certain customers fed at primary voltage, whose requirements are of such a nature as to demand more than the ordinary protection against service interruption on the circuit feeding them but who are located in districts for which the general distribution load does not warrant extraordinary throwover provisions. Such cases may be cared for by running an additional line to their service. This line may be a separate line from the substation, in case of large power customers having one or more separate operating lines, or, for smaller customers, it may merely be a branch off a second power line. Throwover to the spare line may be accomplished by switching arrangements of various sorts on the customer's premises such as oil circuit breakers on each line. Included in this class of load is the type of customer such as a large apartment house, a hotel, a theater, etc., which is served by transformers installed on the premises and for which the load is too large to be tied in to the general distribution secondaries for the district. Such cases may be provided for by use of two incoming primary lines, with the transformers connected to either

one or the other through a double-throw disconnecting switch (or two separate interlocked switches may be used). Fuses may be used to open the circuit on short circuit thus relieving the duty on the switch. The double-throw or interlocking feature prevents the accidental typing together of the two lines. The throwover may be made automatic if desired. Figure 46 shows a diagram of such an installation.

Loop Circuits.—Another development of the reserve circuit scheme which is used to some extent is the "loop circuit" Such a circuit is well adapted to serve a number of fairly large impor-

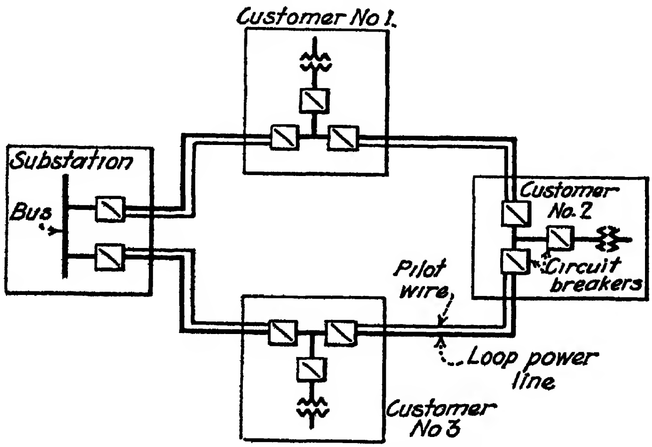

Fig 47.—Loop power line.

tant customers at some distance apart. It also has been used for the primary feed in connection with alternating-current secondary networks. As the name implies, the circuit is in the form of a continuous loop, starting at the sub-station, passing through each of the transformer locations in turn, and returning either to the same substation or to a different substation. Both substation ends are equipped with circuit breakers and circuit breakers are used at each transformer installation to sectionalize the loop in case of trouble. Figures 47 and 48 show two types of such installations. For individual customers not otherwise connected together the type shown in Fig. 47 is necessary, using three circuit breakers at each load point, one on the tap to the load and one in the loop on each side of the tap. Balanced pilot-wire protection is used between the circuit

breakers at both ends of any section. Hence if a short circuit occurs in any section, the breakers at both ends open, that section is killed, clearing the trouble, and the circuit continues to operate as two separate lines until the trouble is repaired and loop operation restored. In case of trouble in the customer's service itself, the circuit breaker on the tap will clear it from the loop entirely.

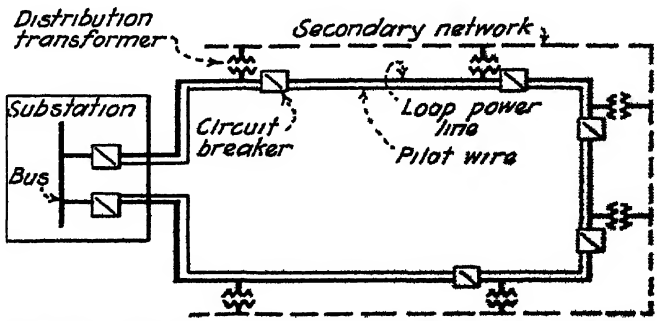

Fig. 48.—Loop power line feeding secondary network.

Where the loop primary feed is used in connection with a secondary network, one of the circuit breakers in the loop at each load point may be omitted, and also the breaker on the tap, if proper protection is provided on the secondary side of the transformer. In this case the transformer installation and the section of the loop from which it is tapped act as a unit, all being cut dead in case of a short circuit either on that section of the loop or in the transformer, Fig. 48.

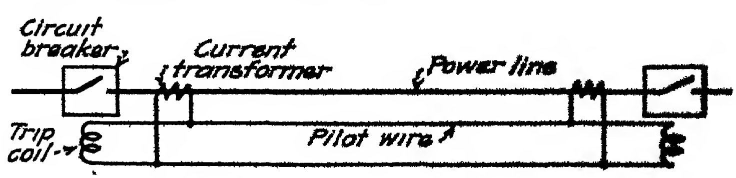

Fig. 49.—Diagram of pilot wire with loop power line.

A balanced pilot-wire protection scheme is diagrammed in Fig. 49. Its fundamental theory is to connect in series, by means of the pilot wire, the secondaries of the current transformers actuating the circuit breakers at both ends of the section of the loop to be protected. As long as the current flows normally in the same direction through both current transformers, no current flows through the trip coils of the breakers. When a short circuit

occurs in the section, however, and the current through one transformer reverses in direction, the result is a current in the trip coils and an actuating force to open the breakers.

Primary Networks.—An arrangement of primary lines which would be very advantageous if it could be worked out practicably and economically is the primary network. So far, however, few schemes of this kind of any appreciable extent have been actually put into operation. The ideal arrangement, as shown on Fig 50, would be with a permanently established, heavy primary ring in the area to be served. This is fed at different points by as many feeders as necessary to carry the load, the number being increased as the load increases. Sufficient reserve feeder capacity

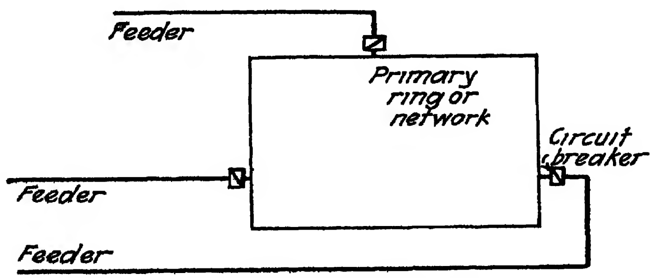

Fig. 50.—Primary network.

must be allowed to enable the load to be carried by the remaining feeders in case one (or more if desired) were to drop out of service. This would provide against interruptions on feeders and could be worked out by use of circuit breakers operated on reverse power at each feeder end where it ties into the primary ring. With the amount of load which it is contemplated might be carried on such a primary ring with several feeders, however, it would be quite essential to provide against total interruption in case of trouble on the primary ring, branch mains, or transformers, and in order to do this it is necessary to use some form of sectionalizing devices to cut off the faulty section. This complicates the problem and partially defeats its main object, even if it is practicably possible to work out a satisfactory arrangement.

The primary network at best is only an intermediate step between simple radial feed and the almost complete protection provided by the multiple feed secondary network. It would provide automatic throwover only for the primary feeders and to

some extent for the primary mains without providing against trouble in transformers and some of that in the primary mains. It would be applicable only to conditions where something better than the radial feed was felt desirable and yet the use of secondary network was not feasible or not warranted. It is doubtful whether such conditions are very numerous, especially those for which effective manual throwover provisions by use of spare feeders are not sufficient.

Voltage.—The choice of the proper voltages for a distribution system depends on a number of considerations. Probably the most important is the economic, which is discussed in some detail elsewhere in this book. The purely economic study, however, must usually be qualified by several other factors, some of which may be economic in fact but of a nature hard to evaluate, others purely arbitrary but fixed by local or other conditions. The chief of these factors are as follows: generally accepted standards, local governmental regulation, physical relations with other utilities, relative reliability, practical considerations of construction and maintenance, voltages used on other parts of the system if a part of a large system is under consideration, and present voltage in use if it is a case of an old system which is being revamped. The latter factor includes consideration of the difficulties to be encountered in changing to another voltage and possible further future change as well as considerations of use of old apparatus and lines to as great an extent as possible.

Occasionally one encounters the problem of selecting the proper voltage for an entirely new system which is not the outgrowth of an older one, in which case the study is somewhat simpler than is the usual case. Ordinarily, however, the question is one of determining the proper voltage for a system which has outgrown its present voltage, either by increase in extent or in load density or both, or else it may be a consolidation of several systems with different voltages for which it is desirable to pick a single standard. Most of the older systems have, up to the past few years, used voltages of the order of 2,200 volts, some even going as low as 1,100 volts. As the loads have increased on these systems and as they have extended out to suburban and rural territory, it has been found extremely difficult practically as well as uneconomical to handle the loads at such voltages. Most of the larger systems are finding it advantageous to change over to a higher voltage, the change to a 4,000-volt Y system being

probably the most popular, but in some places considerably higher voltages are being used.

As a purely economic study, it is not a difficult matter if a certain load is assumed and a certain average length of line is given, to determine the most economical voltage. For the same percentage of voltage regulation and conductor size, line losses, of course, decrease as voltage increases. Doubling the voltage cuts the current in half and therefore reduces the losses to one-fourth as much. On the other hand, costs of line transformers and station apparatus increase with the voltage. Also, beyond certain limits, line costs increase somewhat with voltage due to the necessity for increased insulation, wider spacing of conductors, etc. It is possible to arrive quite definitely at a most economical design as to voltage and conductor size for any given condition in accordance with the principles set forth elsewhere in this book.

For practical purposes, however, it is somewhat difficult to set down all the conditions of the problem in simple, definite quantities. The load density on the system may vary from very concentrated, downtown, city load, to scattered rural customers. It is desirable to limit the voltages used on the system to as few as possible on account of interchangeability and standardization of equipment and materials and construction methods. In fact some of the largest systems have found one standard primary voltage for the whole system a practicable and economical solution, in spite of a wide variation in load densities. The spacing of substations also enters the problem. While a voltage might appear most advantageous for a certain arrangement of substations, a different arrangement and different voltage might give still greater overall economy. Length of circuits will vary considerably in any case. Future load growth must be taken into consideration and an ideal solution is one which not only provides for a considerable amount of foreseen expansion but also is of such a nature that it can be adapted to still further changes to care for the more or less unforeseen, greater growth which may come in the more distant future. The choice of the most advantageous primary voltage must include consideration of these factors on the basis of average values, determined or estimated as exactly as possible.

Standard Voltages.—The generally accepted standards of voltage for distribution primaries are as follows:

Volts	Volts
	6,600
2,300	11,000
4,000[1]	13,200
4,600	23,000

[1] The 4,000-volt circuit is a four-wire circuit with 2,300 volts between phase and neutral Similarly, circuits at 8,000 volts with 4,600 volts to neutral and 12,000 volts with 6,900 volts to neutral are sometimes used.

These are the voltages for which the manufacturers build standard apparatus and the voltage for any new system or changed-over old system should conform to one of them unless there is some very sufficient reason for choosing some other odd voltage. The values given are not rigidly fixed. Voltages within a reasonable range either side of any one of these named may still be considered as belonging to that standard and this is recognized in the rating of most apparatus. For example, 2,300-volt distribution transformers are generally rated for 2,200, 2,300, or 2,400 volts by the manufacturer. As a matter of fact, the voltage designation established for a line or a system is usually more or less of an arbitrary one. A line may leave the substation at 5,000 volts and reach the customer at 4,400 volts and it is a matter of choice as to what value will be used in rating it—4,400, 4,600, 4,800 or 5,000.

The voltages given above in the first column are those most generally used at present for general distribution, but those in the second column are being adapted for distribution purposes more and more, especially for underground lines and rural lines. Until comparatively recently, those 11,000 volts or above were considered as being in the transmission class rather than distribution. However, voltages in the 11,000-volts or 13,200-volts class are now quite commonly used as generator voltages, and if the distribution circuits can be operated at such a voltage, a marked advantage may be gained in the elimination of step-down substation transformers. Voltages of this order are being used in a number of cities to feed underground secondary networks. Voltages in the 23,000-volt class are still usually considered as transmission, but in one case at least, an underground secondary network is fed by primary feeders at 27,000 volts.

4,000 *Volts versus Other Voltages.*—One of the most popular voltages at present is 4,000 volts, three-phase, *i.e.*, applied to a four-wire system with 4,000 volts between phases and with 2,300

volts between each phase and neutral. The neutral wire is nearly always grounded, at least at the substation. The reason for the common use of this plan lies in the quite general use heretofore of 2,300 volts, three-phase, for primary lines. When it becomes advisable to change a 2,300-volt system to a higher voltage, the easiest change is usually to the 4,000-volt, four-wire system. That this is always the best change to make is by no means self-evident. Probably in the majority of cases where 2,300 volts, three-phase has been employed it is the most advisable, even though a later change to a higher voltage may be necessary Where an entirely new system is to be installed or where the old one is not at 2,300 volts, the use of 4,000 volts is of questionable advantage. The matter should be given some study before the change is decided upon, however, and all advantages and disadvantages carefully weighed.

The advantages of the 4,000-volt system as applied to the revamping of an old 2,300-volt system are as follows:

1. The voltage from phase to neutral remains the same as before, *i.e.*, 2,300 volts. If the old system were operated with a grounded neutral, the voltage to ground would, of course, be increased. If operated ungrounded or with one phase grounded, the new system is in effect at the same voltage. In any case, the line insulation is usually sufficient without change and the new system requires only the addition of a fourth wire to the primary feeders. Sometimes the spacing between wires is left unchanged (ordinarily about 14 in.) but in some cases the increased voltage between phase wires has caused increased trouble due to adjacent phase wires whipping together. This can be remedied to a considerable extent by wider spacing between the adjacent phase wires (4,000 volt).

2. The phase-to-neutral voltage, being the same as the old phase-to-phase voltage, the old distribution transformers can be used without change, being connected at 2,300 volts from phase to neutral. Three-phase installations are made with three single-phase transformers, connected in Y, or may be made with 4,000-volt transformers in Δ. The advantage in using the old transformers is usually a major one, as the cost of replacing transformers for a higher voltage is a considerable item.

3. The phases can be regulated separately by single-phase regulators at the substation, thus keeping the voltage well balanced in spite of unbalanced loads.

4. Substations may often be rearranged utilizing the old apparatus, since the new voltage to ground is 2,300 volts, the same as the old. For example, single-phase 2,300-volt transformers which were formerly used in Δ may be connected in Y.

5. The difficulties of making the changeover in the field are much less using the old equipment and lines and the same voltage to neutral than if an entirely different voltage with all new equipment were introduced.

6. The load which can be carried by a 4,000-volt feeder with large-sized cable or wire is claimed by some to be all that should be tied up on one feeder.

In contrast to the above advantages there are certain very marked disadvantages in the 4,000-volt system, as compared with higher voltage systems, which must be considered even in making a changeover from 2,300 volts, and which it is believed, make its use rarely advisable for a new system, or one not using 2,300 volts previously. These are as follows:

1. The phase-to-neutral voltage being only 2,300 volts, single-phase branches off the three-phase feeder are at a comparatively low voltage, *i.e.*, only the feeder has the advantage of the higher voltage. Where the load is concentrated in a comparatively small area and branches are short, this may not be a serious disadvantage, but where the branches are long, as in suburban or rural territory, it may become of major importance in limiting the length of such branches or the load which can be carried with a reasonable voltage drop. At the same time, larger power losses are experienced than with higher voltage on these branches. A remedy would be to use 4,000-volt branches, but, in this case, 4,000-volt distribution transformers must be used which necessitates a change from old equipment.

2. Since the percentage of power loss and of voltage drop for a given load and wire size vary approximately inversely as the square of the voltage, the difference between 4,000 volts and 6,600 or even 4,600 may represent a considerable economy and advantage for the higher voltage. Figure 51 shows the relative loss and voltage drop for different voltages. Since, as shown on Fig. 52, distribution transformer costs do not rise in proportion to the voltage until above 6,600 volts, if new transformers are to be purchased, the higher voltages (even higher than 6,600) may show considerable economy when overall costs, including losses, are studied.

3. If 4,000 volts should become inadequate due to future large increases in load, the system is not adapted to further increase in voltage without complete change, whereas a 4,600-volt system,

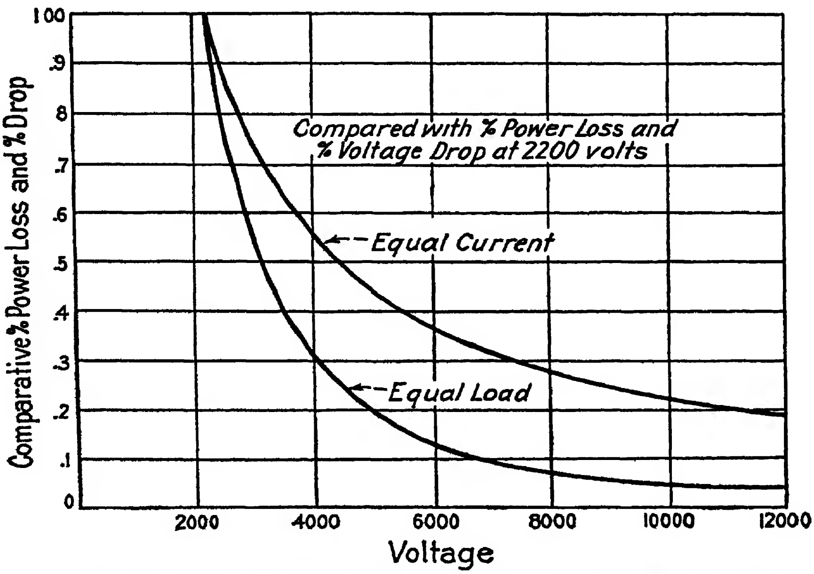

Fig. 51.—Comparative per cent power loss and per cent voltage drop at different voltages

for example, may be quite readily converted to an 8,000-volt system if it ever becomes necessary. In that case, of course, it

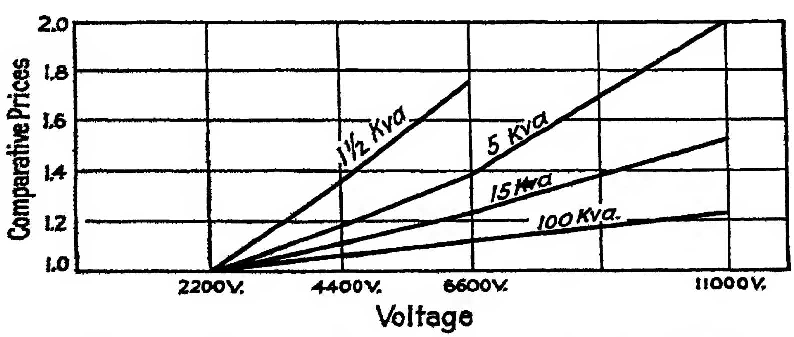

Fig. 52.—Comparative costs of distribution transformers of different voltage ratings.

must be recognized that most of the disadvantages here given for 4,000 volts may be applied to that change also.

The use of three-wire, three-phase circuits at 4,600 volts, 6,600 volts, or 13,200 volts avoids most of the above difficulties charged against the 4,000-volt, four-wire system and may prove economical, although the other considerations, applying to higher voltages, mentioned elsewhere in this chapter, must be taken into account.

Grounded Circuits.—It may be appropriate here to discuss somewhat the question of using circuits with grounded neutral *versus* those with the neutral ungrounded. On many systems, the neutral of the primary circuit, whether or not it is brought out as a four-wire circuit, is grounded at the substation. The advantages of this practice are that the voltage to ground on the line insulation, transformer bushings, etc. is definitely limited to the lowest possible value. Also, if an accidental ground appears on any phase it is immediately cleared by the opening of the circuit breaker and will not spread trouble to other circuits on the bus or hold on as an arcing ground, possibly causing other more serious troubles. On the other hand, service on an *ungrounded* circuit is not interrupted by every accidental ground which may appear. Probably less trouble is experienced due to tree contacts, etc. Such circuits may be operated for hours or sometimes days until the ground is located and cleared. Somewhat greater safety is assured linemen working on hot wires or transformers, since an accidental ground through their body will not be a dead short unless accompanied by another accidental ground at some other point. This point is sometimes questioned, in that the linemen may depend too much on the transformer cases being ungrounded, and not protect themselves sufficiently against accidental grounds.

Common Grounded Neutral.—In connection with the four-wire primary (4,000 volt) it is sometimes the practice to use the neutral of the secondary as the primary neutral also, making the secondary neutral continuous for this purpose. This eliminates one wire and is hence apparently an economical practice. However, the separation of the neutral from the phase wires, and also the fact that it is grounded all along its route allowing part of the neutral current to flow through the ground, tends to increase the inductive effect on parallel telephone circuits where such effects are troublesome. Also there is a tendency in some quarters to look with suspicion on the use of a secondary conductor for primary current in any sense. The practice is prohibited by law in some states at present. The scheme has been employed

in some localities for several years, however, and reports on the experience with it have not indicated any undue amount of difficulty or danger in connection with its use.

Local Governmental Regulations.—It is quite often the case that the municipal or other local authorities in the territory in which the lines are located have either formulated regulations or at least have quite definite ideas as to the maximum voltage which should be used on overhead lines in their districts. Whether or not these regulations agree with the desires or judgment of the distribution engineer or even with accepted good practice, they should usually be given respectful consideration, if not from compulsion, at least as a matter of public policy and the maintenance of amicable relations. It must be remembered that to the uninitiated public the danger from electric lines is generally felt to be in direct proportion to the voltage, whereas, within certain limits this is likely not to be the case. As far as the danger to the public from coming in contact with line wires is concerned, a line at 13,200 volts is not to any considerable degree more dangerous than one at 4,000 volts or even at 2,300 volts except that, at the lower voltages, the weatherproof insulation, if present, may, in certain cases, offer some protection (by no means to be depended upon, however).

The National Electrical Safety Code, which is the basis of state rules in a large number of states, requires greater safety factors for construction with lines at the higher voltages (over 7,500). The additional cost thus incurred must not be lost sight of in considering the economy of higher voltages.

Physical Relations with Other Utilities.—It must be borne in mind that the power company's lines must nearly always occupy the same streets, if not the same poles, with the lines of other utilities, telephone, telegraph, possibly other power companies, etc. The physical clearance between such wires at crossings or on the same structures is governed by the voltage, both on account of practical considerations of construction and operation and also usually by governmental regulations where such exist.

A more serious consideration in the use of the higher voltages is the fact that inductive effects of power circuits on signal circuits increase with the voltage of the former. The telephone interests have in most cases objected to the practice of joint construction of power and telephone circuits on the same poles where the power voltage is over 5,000 volts. At the present time, the whole mat-

ter is under consideration by a joint committee of the two interests and it is probable that eventually some definite settlement will be agreed to by both parties as to what voltage, if any, should be considered an upper limit and possibly what accepted measures of protection should be adopted with the higher voltages. In view of the quite general practice of joint construction, it would seem that the use of distribution voltages in the higher range must be eventually accepted. At present, however, any company contemplating such use must expect opposition, at least for such lines as may be on joint poles. Aside from the considerations pertaining particularly to joint construction, although inductive effects on parallel signal circuits do increase with voltage, the difficulties are usually not found to be particularly serious for voltages up to 13,200, especially if a reasonable amount of attention is paid to inductive coordination. For higher voltages, parallels are not at all impossible, but their practicability depends considerably on the type of circuits involved, separations, etc.

Reliability.—In general, it may be said that reliability of service decreases as distribution voltage increases unless measures are taken to compensate for it. Outages on overhead lines are due in large part to wires swinging together, swinging into trees or otherwise being accidentally grounded, shorts or grounds by kite strings, etc.

Up to 2,300 volts to ground, the ordinary weatherproofing commonly used on wire, if in good condition, is more or less effective as an insulation, especially when dry. This prevents a great many of such outages by insulating the wires from each other or from trees etc, on these momentary contacts. At voltages higher than this, the weatherproofing becomes less effective and hence, as may be expected, the troubles from these causes increase. Above 4,600 volts it is doubtful if weatherproofing is of any appreciable value for this purpose and even at that voltage it is of little use except when perfectly dry.

On underground lines, the higher the voltage the greater the stress on the cable insulation and, in general, the greater the possibility of its failure, especially as the higher range of voltages is reached.

In general it will be found necessary when the voltage is raised on an old circuit either overhead or underground, unless provision has previously been made for such a raise, to take steps to counteract the increased trouble. Such steps are the increas-

ing of insulation, increasing spacing between conductors, adding more reserve lines, clearing up bad tree conditions, etc.

Construction and Maintenance.—When the new voltage is very much higher than the old one, complete reconstruction of existing lines may be necessary instead of a minor revamping. This must be taken account of in studying the economies of the problem. Aside from this, the difficulties to be encountered in erecting and working on or about such circuits will usually increase with the voltage. Beyond certain limits, usually about 4,600 volts, the lines cannot be worked on when live with any degree of safety, unless special tools are used. If such tools are necessary or if the lines must be shut down, inconvenience, delay, and unforseen expense is a practically certain accompaniment.

Conductor Size.—The proper size of conductor to use in any particular situation depends chiefly on three conditions:

a. Economy.
b. Voltage drop
c. Mechanical design.

The most *economical* size of conductor for a given load can be determined by a study of annual costs on the construction and energy losses, as shown in another section of this book. Such a study is very helpful in choosing the proper size whether or not it is the determining factor, since a size as near as practicable to the economical can still be selected even though it is limited by other considerations.

The allowable *voltage drop* over the line will limit the size of conductor to a certain minimum. If this limit is greater than that determined by economy, economy must be disregarded to that extent; if it is less, the economical size should be chosen ordinarily. Computations for voltage drop are given in Chap. X.

Mechanical strength of the conductor and of supports impose certain limitations. As a rule, in heavy loading districts (National Electrical Safety Code) a conductor smaller than No. 6 medium hard copper is not to be recommended. On the other hand, conductors larger than No. 0000 are rather difficult to handle on the ordinary pole line without special provisions for supporting structures, guying, etc.

As a rule, the sizes of conductor should be limited to as few a number as possible to avoid difficulties in carrying stock, ordering, etc.

CHAPTER VII

SECONDARY DISTRIBUTION

Since the majority of loads are serviced at voltages of the order of 115 or 230 volts, and since on alternating-current systems the distribution from the substation is usually at a much higher primary voltage, some form of secondary link (and transformer) will ordinarily occur between the primary and the customer's service. The secondary may be of any of the following types:

1. Individual transformer for each customer with direct secondary connection (separate service).
2. A common secondary main, fed by one transformer supplying a group of customers (radial).
3. A common continuous secondary main, fed by several transformers all of which are connected to the same primary feeder (secondary bank).
4. A common continuous secondary main, as in (3) fed by several transformers, with these transformers divided among two or more primary feeders for their source of supply (alternating-current low-voltage network or secondary network).

Each of the above types of secondary distribution have their particular province. They will be further discussed, in order.

Separate Service.—The separate feed for each customer, Fig. 53, is distinctly applicable to certain loads such as the isolated service, the service of a different character from those general in the surrounding districts (three-phase service in a single-phase area, etc.), and the very large load. In other cases, some study may be required to determine whether the separate service or the group main is preferable.

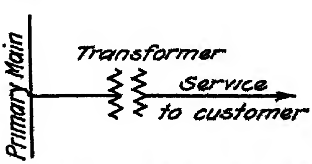

FIG. 53.—Separate service.

On rural distribution, for example, customers are usually spread out so far apart that any considerable amount of secondary main is impracticable. Where two or three are grouped fairly close together, however, there may be a question as to whether separate transformers should be used for each, or secondary main run from a common transformer. Two considerations usually govern.

First, the cost of the common transformer and the secondary main may be compared with the cost of the separate transformers, including, of course, the cost of losses on both transformers and secondary main. Second, the allowable voltage regulation may be a factor. If the system is designed and operated on the assumption of no secondary drop between transformer and service, the introduction of any considerable amount of such secondary in certain cases may give too low voltage at the service under some conditions.

Another case for which the solution is not always evident is where a load occurs which is considerably larger than the average run of loads in the district in which it is located, such as an apartment house in a district with otherwise comparatively light load. In order to give good voltage conditions at such a service (allowing for a fair amount of drop in the customer's wiring), any considerable amount of voltage drop in secondary mains is usually not allowable. With the light mains suitable for the general distribution load, this requirement necessitates that the transformer be located at or immediately adjacent to the large service. On the ordinary radial secondary main fed by one transformer, the location of the transformer at the large service may in some cases be satisfactory for the rest of the load, but oftener it is very likely not to be so. In such a case, an entirely separate installation may be preferable to a rearrangement of the secondary. Where secondary banks are used, a further question arises. If the large transformer placed for the large load is tied in to the secondary mains, a reserve source of supply in case of its failure is provided but sufficient transformer capacity must be present in adjacent transformers to furnish that emergency reserve without overloading them unduly. In case the general distribution is comparatively light, this may require a major increase in transformer capacity amounting to almost duplication of the capacity installed for the load. An entirely separate installation for the large load is indicated in such a case unless the emergency supply is of sufficient importance to warrant the extra expense and cannot be otherwise obtained more conveniently.

Where the general distribution load is very heavy, requiring large transformers and secondary mains, the need for separate services, even for loads of considerable size, becomes less evident since secondary voltage drop is likely to be comparatively small on such systems.

In general, separate services are somewhat wasteful of transformer capacity since no advantage is taken of the diversity factor between customers' loads. The transformer should, as a rule, be located as near as practicable to the point of service to reduce the length of secondary and its losses to a minimum.

Radial.—The most usual form of secondary arrangement for general distribution is that in which a group of customers, usually of more or less similar characteristics, is fed by a common secondary main, supplied by a single distribution transformer see Fig. 54. Where polyphase and single-phase loads both occur intermingled, the secondaries serving each type are quite ordinarily kept separate. Combined secondaries have some use, however, and will be discussed in some detail later on.

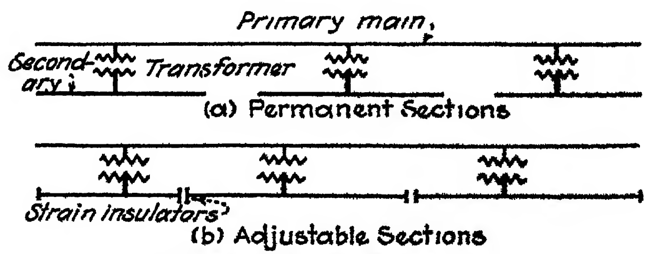

Fig. 54.—Radial secondaries.

This type of secondary has the advantage over the "separate service" of utilizing the diversity between the demands of individual customers in reducing the total transformer capacity necessary. Also for small individual loads, it allows transformers of larger capacity to be used which, as a rule, cost less per kilovolt-ampere than would smaller individual transformers. The larger transformers also have the faculty of absorbing starting currents of motors on individual service with less resulting voltage dip than would be the case with the small transformers.

Compared with secondary bank or network (discussed below), the radial type of secondary has the advantage of simplicity. Any trouble in transformer, secondary, or services is localized to that one section of main and is not likely to spread to other sections of the secondary system. A positive indication of trouble in transformer, fuses, etc. is given by the interruption to service on the section. The circuit is simple, involving only one transformer and one secondary main and hence calculations for transformer size and location, voltage drops, etc. are compara-

tively easy. The transformer may be loaded as heavily as is consistent with safety and with good voltage regulation (see Chap. IX, transformers) without regard to the size of adjacent transformers or their loads. On the other hand, this arrangement makes no provision for maintaining uninterrupted service in case of transformer failure or broken secondary wires. Also it is relatively inflexible. Any increase in load on a section of secondary is thrown entirely on that section and its transformer and must be met by increased transformer capacity and sometimes also by increase in conductor size. If additional transformers are installed, the secondary must be redivided to create additional sections. Similarly, heavy concentrated loads impose all their duty upon the single transformer and section of secondary on which they occur without help from adjacent sections. In general, no advantage is taken of the diversity in demands on adjacent transformers.

In laying out a *radial* system the tendency is to establish the sections more or less permanently according to geographical limitations and load grouping, present or probable, such as a section to a city block, for example. The transformer location in the section is similarly established and size of transformer and of secondary mains designed accordingly to serve the expected load. The alternate of this method, where it is feasible to employ it, is to lay out the secondary as more or less continuous, cut into sections with strain insulators as conditions require. The transformers are placed along the secondary in the most advantageous positions in regard to the load and such positions, and hence the division points in the secondary, are changed from time to time if necessary to meet changing conditions. The latter form of layout may be better adapted to the use of the theoretically most economical sizes of wire and transformers but is not always practical on account of limitations on available transformer locations. A combination of the two forms is perhaps the most generally applicable, *i.e.*, the establishment of more or less definite sections of secondary and transformer locations, with some provisions for change later if the necessity arises. In laying out secondary distribution in sparsely built-up districts, it is often advisable to install only part of the transformers planned for the eventual system, *i.e.*, to let each transformer feed not only its own section of main but also one or more adjacent sections, postponing the installation of transformers in those sections until

the load builds up. This does not prevent definite transformer locations for the eventual system being chosen, however.

Secondary Banks.—The use of *secondary banks* is a step toward the provision for uninterrupted service to the customer. A *secondary bank* consists of a continuous secondary main fed by more than one transformer, but with all the transformers supplied by the same primary feeder, see Fig. 55. In reality, this is one form of secondary network and is sometimes called a "single-feed network." It seems preferable, however, to dis-

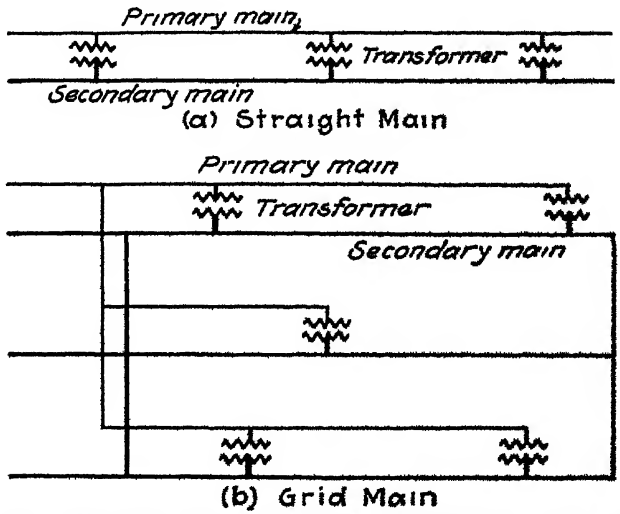

FIG. 55.—Secondary bank: (*a*) Straight main; (*b*) Grid main.

tinguish it as above, since that name is quite commonly used and the term "secondary network" has come to be generally understood as applying to the "multiple-feed network" described below. The secondary bank may take the form of a long straight section, a loop, a grid, or a combination of these. In any case the principle is the same, and with proper attention to design the same advantages and disadvantages apply.

The chief points of advantage accomplished by the *secondary bank* are as follows:

1. In case of the failure of any transformer, its load is carried by adjacent transformers, with perhaps some reduction in voltage but without interruption of service, until the faulty equipment is replaced.

2. Better distribution of load among the various transformers. A heavy load coming on at any point is shared, to some extent,

by at least two and possibly more transformers instead of being all thrown on one.

Normal distributed load is automatically divided among the transformers giving the highest possible voltage at the low points, which, with theoretically evenly distributed load of the same density, would fall exactly half way between any two transformers (if they are of the same size). Under actual conditions, of course, with loads of various sizes and varying characteristics, these low points may fall almost anywhere along the secondary.

3. Better average voltage conditions resulting from such load distribution.

4. General increase, in load may be cared for by increasing the size of part of the transformers in the bank without increasing all of them. This is of material advantage with a limited number of stock sizes of transformers. For example, if 15-kv-a. transformers are used, a general load increase, which would overload all the transformers in the bank, might be handled satisfactorily by replacing every other one with a 25-kv-a. for the time being, until further increase made the replacement of the other transformers necessary.

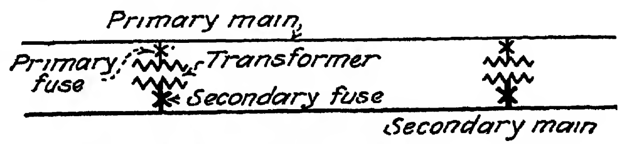

FIG. 56 —Location of fuses—secondary bank

5. Similarly, load increases, either general or individual, may be cared for in some cases by installing additional transformers at intermediate locations between other transformers, without disturbing the present arrangement.

6. More capacity is available to burn clear a secondary short circuit if one occurs. This may often be done without blowing secondary fuses and hence without interrupting service.

7. Some advantage is taken of diversity between demands on adjacent transformers in reducing the total transformer load.

Secondary fuses (or other form of automatic circuit breaker) must be used with each transformer connected to a secondary bank in order to clear the transformer from the bank in case of a short circuit in its windings. In such an eventuality, the fuses are blown by current fed back into the transformer from the secondary main. In the true secondary bank, these fuses are located between the transformer and the secondary main, thus leaving the main clear and with uninterrupted service in case the fuses blow, see Fig. 56.

On this system, reserve transformer capacity must be provided in each transformer since it is contemplated that the load of a faulty transformer will be carried in emergency by its neighbors. Such reserve capacity will often be found, at least partially, in the safe overload capacity of the transformer which is not utilized under normal operating conditions due to considerations of voltage regulation (see Chap. IX). The voltage in the vicinity of the faulty transformer may be low in such an emergency but it is of some advantage to maintain service, even at low voltage, and the drop in voltage will usually be sufficient indication of trouble to bring in reports of it from customers.

A form of layout sometimes called a secondary bank utilizes a secondary sectionalizing fuse midway between transformers instead of a fuse between transformer and secondary main, see Fig. 57. These sectionalizing fuses are of small capacity and their function is to blow whenever an abnormal amount of current passes through them. That is, in case of the failure of a transformer, the sectionalizing fuses would clear not only the transformer but also all of the section of secondary main normally fed by it from the system, interrupting service on that section. It is evident that this plan, although having some of the advantages of the secondary bank in the better distribution of load and voltage under normal conditions, lacks one of its chief features, the possibility of maintaining uninterrupted service on the secondary. It is not essentially different from the radial plan, previously described, except in the substitution of a light tie in the form of a small fuse instead of absolute separation between sections of secondary main.

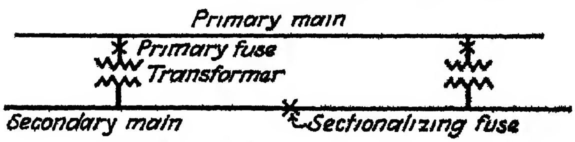

FIG. 57.—Sectionalizing fuse.

A disadvantage of the secondary bank is the possibility of cascading, *i.e.*, in case one transformer goes out, of having the adjacent transformers also go out, being loaded beyond their fuse capacity or being burned out by excessive overload. The increased overload is then passed on to other transformers, causing them also to go out and an interruption occurs on the whole bank. The danger of this occurrence can be minimized by the proper arrangement of the bank, proper fusing and proper sizing of transformers, both individually and in relation to adjacent transformers.

In laying out a secondary bank, the following points should be observed:

1. The grid form, with cross-ties at convenient points, is preferable to long single mains.

2. It is preferable to have the bank so arranged that in case any transformer drops out, its load will be fed directly from at least two other transformers. In case physical conditions make this impossible, the sizes of the transformers must be specially considered to prevent cascading.

3. Transformer sizes should be such that the load of any faulty transformer can be picked up by the others without undue distress. This does not necessarily mean that all transformers must be loaded normally to only two-thirds of their rated capacity even on overhead banks, however.

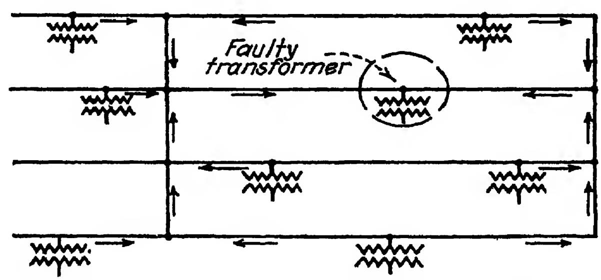

Fig. 58.—Secondary bank—division of load of a faulty transformer

It is a difficult problem to determine accurately just how the load of any faulty transformer will divide among the others with a grid form of network (see also Chap. IX). The actual load (lighting load) of the faulty section is, of course, reduced somewhat by the reduced voltage. This is not in proportion to the reduction in voltage but to its 0.6 power, approximately, so this effect is not so marked as it might appear at first glance. The division depends on the impedance of the various paths through the secondary grid by which the load may be fed, including transformer windings as part of these paths, see Fig. 58. These impedances vary with the size of the transformers, their distance apart, and the size and spacing of secondary.

The arrangement along the secondary of the various individual loads and the normal load on each transformer also have an effect. It may be said, however, that ordinarily with overhead lines, the impedance of the secondary between transformers is likely to be relatively high compared with that of the transformers themselves, resulting in a large proportion of the load of any faulty transformer (probably 70 to 80 per cent) being thrown on the

transformers immediately adjacent. With underground lines, on the other hand, the impedance of the secondary cables is likely to be relatively low in comparison with the impedance of the transformers. This makes for a more equitable division of the load among all the transformers in the *bank*. If the transformer impedance is deliberately raised until it predominates that of the secondary mains (as is often done with *secondary networks*) the division is still more improved and the stress on the transformers immediately adjacent to a faulty one thereby relieved. In such a case, the total reserve capacity in the *bank* may be counted on rather than that in adjacent transformers only.

The relative amount of the load of the faulty section picked up by each adjacent transformer on an overhead system or by each transformer on an underground system depends to a considerable extent on the relative impedances of the transformers. If the transformers are of similar or nearly similar characteristics (per cent X and per cent R the same) they could be paralleled on any load without intervening secondary and would divide the load in accordance with their size without overloading either (see Chap. IX). Paralleling these same transformers with intervening secondary does not alter the case greatly. Hence it may be said that the practice of using transformers of different sizes in the same bank, even if those sizes are quite widely different, is not necessarily objectionable, provided they are of proper characteristics to allow being connected in parallel. What must be carefully considered, however, in such a case is the provision of sufficient reserve capacity in such transformers to carry the emergency load safely. For example, a 100-kv-a. and a 5-kv-a. transformer in the same bank might be safe enough if there is provision for carrying the load of the 100 in case it goes out, but a 100-kv-a. transformer with a 5-kv-a. transformer on either side of it and no other capacity immediately adjacent would be very bad practice.

The necessary reserve capacity may be found to a considerable extent, especially on overhead systems, in the overload capacity of the transformers for comparatively short periods. This is discussed in more detail in Chap. IX. The sizes of fuses used with the transformers must be so chosen as to allow for the use of this emergency capacity (see Chap. XII).

Secondary banks are not very commonly used although they have been adopted on some of the largest systems. They are more applicable to overhead distribution than to underground

since they are adapted to use in areas of comparatively light-load density (for which overhead is the prevailing system) where multiple-feed networks are not justified by the character of the load and not practicable on account of the expense and congestion of lines resulting from the large amount of duplication of primary feeder and mains which would be required in such an area. Furthermore, since troubles are more quickly located and repaired on overhead lines than on underground, the fact that the *secondary bank* provides only against transformer failure, and to some extent failure of secondary mains, but does not provide against faults on primary mains or feeders is not of such great importance.

Secondary Networks.—*Alternating-current Low-voltage Networks.*—The demand for a type of alternating-current distribution to give a very high degree of reliability of service has led to the development of the *secondary network* or *alternating-current low-voltage network* as it is often called. Strictly speaking, any interconnected group of secondary mains fed by more than one transformer falls within the class of such networks, including the secondary banks previously discussed. However, the term "secondary network" has come to be quite generally understood as applying specifically to the multiple-feed network, or the network supplied by more than one primary feeder. It will be used here in that sense, single-feed networks being designated, as has been stated, as "secondary banks."

The object sought in the use of secondary networks is the insurance, as far as possible, against interruptions to service, even those of short duration. The secondary bank provides to a large extent against trouble on transformers or secondaries, but leaves the service dependent on a single primary feeder. Hence the reliability of service is no greater than that of that feeder. With the secondary network, provision is made against feeder interruptions as well, by supplying the network from more than one feeder. In case of trouble, the faulty feeder is automatically disconnected, leaving the other feeders to carry the load. In this way a high degree of reliability is assured, since provision is made against interruptions due to trouble on primary feeders, primary mains, transformers, and secondaries. Except for possible trouble in the customers' own wiring, the service reliability with a well-designed network is hence of the same order as that of the substation from which the primary feeders come and this may be made very high if desired.

Secondary networks are particularly applicable to areas of dense loading such as the downtown districts of large cities, where the character of the load is such as to demand continuity of service and where the revenue is such as to warrant extra expenditures, if necessary, to attain it. Also, it is usually the case that such areas are, of physical necessity, fed by underground distribution and for underground distribution a higher degree of reliability is demanded than for overhead on account of the relatively greater difficulty in locating and repairing trouble when it occurs. Formerly it was considered that service of the type demanded by such loads would be given only by the extremely reliable direct-current network. It was to provide a similar character of service in alternating-current territory that the secondary network was developed and finds its chief field. It is doubtful if its use can often be justified in areas of low-load density where service continuity is not of prime importance or where only an occasional large load is of such a nature. Other methods can be used for the individual load.

Considerable confusion and misunderstanding has arisen in the discussion of secondary networks in the past due to two factors. First, the alternating-current network has been often compared with the direct-current network to the apparent disadvantage of the latter in the matter of cost. This has been assumed to indicate that it was proposed that present direct-current systems should be replaced by alternating-current, which has not met with much favor by those operating large direct-current systems. It is quite natural that the two should be compared, since the direct-current network is the standard of reliability toward which the alternating-current network is aiming. In showing costs, the two have usually been compared on the basis of original cost only. With an established direct-current system, the cost of replacing direct-current equipment with alternating-current would often be prohibitive even if all other factors favored a changeover. In some cases where the direct-current area is a comparatively small part of the total, or where the load is of such a nature that the replacement costs are not excessive, a complete changeover has been found advantageous from the standpoint of unification of the system as well as economy. This question has been further discussed in some detail in Chap. V under "Direct Current."

The second factor has been the confusion in the relation between *secondary networks* and *combined secondaries for light and power.* This has arisen on account of the fact that *combined secondaries* are particularly well adapted to the conditions under which *networks* are also advantageous, hence most of the networks installed have used combined secondaries. However, it should be noted that the network principle of operation does not involve as an essential part of the design any particular type of combined secondary or combined secondaries at all. It is just as applicable

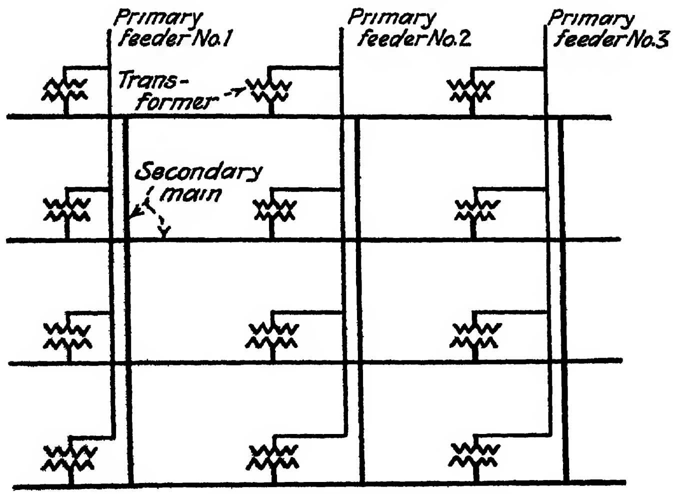

FIG. 59.—Secondary network.

to separate systems of single-phase and polyphase secondaries. Combined secondaries will be discussed later. The term "secondary network" should be clearly understood as referring only to that type of distribution in which a continuous secondary main is fed by several transformers which in turn are supplied by more than one primary feeder (alternate transformers on different feeders, etc.) with provisions made for automatically disconnecting a faulty feeder or transformer from the secondary in case of trouble, see Fig. 59. Questions of the type of secondaries, voltages, type of primaries, protective apparatus, etc., while involved in the design of any particular network, are not fundamental to the network principle, but are merely details of design. If the type of load and character of service is such as to make a network advisable, there are various forms in which

it may be worked out and which have been used satisfactorily in certain cities.

The general advantages of network operation in providing against transformer failure, giving better distribution of load among transformers and better distribution of voltage along the secondary, have been given under secondary banks. Also the division of load among the transformers on a network was discussed to some extent. The same points apply to the multiple-feed *secondary network* as well and need not be repeated here. Certain other special features of such networks will be taken up below.

Primary Feeders.—The type of feeder which has been most used so far is the ordinary radial type. Several of these are run into the area to be fed and the transformers in the area connected alternately on different feeders as far as practicable, see Fig. 59. From three to five feeders are usually run to one network. With this system, the transformers are tied in to their feeder, either solidly or through non-automatic disconnects, the protective apparatus being placed on the secondary side between the transformer and the secondary mains and designed to disconnect the transformer on reverse flow of current. In this way, a feeder and all its transformers act more or less as a unit and a short circuit on the feeder or in any of its transformers operates to disconnect the feeder and all of its transformers from the network, leaving the other feeders to maintain the service. It is evident that sufficient transformer capacity must be provided on the network so that any one feeder can drop out without overloading the remaining transformers. For example, with four feeders on a network, the excess capacity must be 33 per cent (theoretically) with five feeders 25 per cent, etc.

Another type of feeder which has been used is the loop feeder. Such feeders have been previously described in Chap. VI, see Fig. 48. Several loop feeders may be tied into one network for additional primary protection, although each loop has the possibility of feed from both ends radially if any section drops out. The advantage of the loop primary is that less transformer capacity is put out of service in case of failure of one transformer or one section of feeder. With the loop, such trouble affects only the particular section of the loop and the one transformer connected to it, whereas with the radial system, one whole feeder and all its transformers are affected. The chief disadvantage

lies in the necessity for using oil circuit breakers at primary voltage to sectionalize the loop.

The tendency has been to go to higher voltages for the primary feeders to *secondary networks* than has heretofore been considered desirable for city distribution; 13,200 volts is being used in several places. One reason is that although primary failures may be increased by the increase in voltage, with the multiple feed, continuous service is maintained by the other feeders in any case. Also, with the radial system, primary fuses, which have been a serious problem at the higher voltages, are omitted. A third reason, in several cases at least, has been the economy obtained by running feeders at generator voltage (13,200 volts) direct to the distribution transformers without intervening transformation, thus eliminating a large part, if not all, of substation cost. In one case at least, feeders of different voltages, *i.e.*, old feeders from a step-down substation and new feeders direct from the generating station have been tied into the same *secondary network*.

Transformers.—In most cases, with radial feeders, it has been found advisable to use a higher reactance in the transformer than is ordinarily used on distribution service, *i.e.*, a reactance of the order of 10 per cent. This acts to distribute the fault current fed into a secondary short circuit, or into a faulty feeder, and also the load dropped by such a feeder after disconnection, more uniformly among the other transformers on the network, rather than imposing extremely heavy duty on the transformers nearest the fault, as is the case when the reactance of the secondary mains predominates that of the transformers.

Such additional reactance is sometimes incorporated in the transformer and sometimes added externally.

Protective Apparatus.—The device most commonly used to disconnect the faulty transformers from the network consists of an air-break circuit breaker, actuated by a system of relays which causes it to open on reverse flow of current (into the transformer from the secondary mains), even current of the order of the exciting current of the transformer, and also causes it to close in again on the network when normal conditions are restored on the feeder and transformer. With such a device placed between each transformer and the secondary mains, all transformers connected to any one feeder will be disconnected, in case of a short circuit on the feeder or any of its transformers, by reverse

flow of short-circuit current from the network to the faulty feeder through all of its transformers. Also, if the feeder is opened, either by a break or intentionally by opening the station circuit breaker, all of its transformers will be disconnected from the network by the flow of charging current from the network. On restoration of normal conditions of voltage, phase sequence, etc. (such as closing the station breaker in the above case), all the transformers are reconnected to the network. Use of this feature is sometimes made to disconnect part of the feeders from the network during lightly loaded periods, thus saving the core loss of their transformers.

Some use has also been made of oil circuit breakers instead of air-break switches, also of non-reclosing protection, *i.e.*, such that the breakers open only on flow of short-circuit current of some magnitude (not charging current) and stay open until reclosed by hand. It is claimed by some that such a system is more rugged although lacking the convenience of operation and flexibility of the previously described apparatus.

Fuses are used to some extent but, due to their inherent lack of accurate selectivity, are not usually satisfactory for disconnecting transformers from the network, especially with the radial type of feed.

Secondary Mains.—Much of what was said concerning the design of the secondary main system under secondary banks is equally applicable to the secondary network now being discussed. Reference should be made to that section as the points will not be repeated here.

The size of the secondary mains and their arrangement should be carefully studied in connection with the transformer installations with the view to: (*a*) properly divide the normal load among the transformers; (*b*) properly divide fault current among the transformers; (*c*) provide good voltage regulation to all customers; (*d*) provide for burning off short circuits or grounds at any point without interrupting service in case sectionalizing fuses are not used or for positively clearing such faults by sectionalizing fuses if they are used.

In several of the recent network installations no sectionalizing or branch fuses are used on the secondary. All branches, services, etc. are tied in solidly, and short circuits or grounds, in case they occur, are expected to burn clear without interrupting service to the network. Transformer sizes and cable sizes must

be properly proportioned if this action is to take place satisfactorily.[1]

Fairly large cables, 200 to 500 M. cir. mils are used ordinarily, and in most cases single conductor

As has already been stated, in districts where secondary networks find themselves best adapted, the use of combined secondaries for serving both light and power is usually advantageous. From the point of view of the design of the distribution system only, the Y-connected, three-phase system of combined secondaries is the most suitable since there is no separation of phase-areas for the single-phase load, and load balance in the three phases is more easily maintained. Other considerations, however, may favor the delta-connected scheme, two-phase, or separate secondaries for light and power, and all these plans have been used successfully with network operation. The various types of combined secondaries will be discussed in a following section. Since the question of service voltages is seriously involved in the problem of combined secondaries, the general subject of secondary voltage will be taken up first.

Bibliography

The following is a list of some of the articles which have appeared in recent years dealing in whole or in part with secondary networks. They are recommended to the reader who is interested in the details of the application and design of such networks since only a brief summary has been possible in the preceding paragraphs

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[1] Kehoe, A. H., "Underground Alternating-current Network for Central Station," *Trans.*, A.I.E.E., Vol. 43, p. 844.

Electric Journal, Vol. 22, No. 7, p. 316–351. Articles by A. P. FUGILL, G. G. GRISINGER, C C. HUDSPETH, E. E. LEHR and H. RICHTER on various phases of secondary networks.

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Serial Report of Electrical Apparatus Committee, National Electric Light Association, "Alternating-current Low-voltage Networks," N.E.L.A. *Pub.* 256–236; also in *Trans.*, A.I.E.E. for 1926 under "Annual Report of Electrical Apparatus Committee."

Secondary Voltage.—Secondary voltage standards for a system are not subject to a wide range of choice. For residence and commercial lighting service, the customary standard is of the order of 115 volts (110 to 120) with 230 volts between outside wires if three-wire, single-phase circuits are used. This has become the generally established practice in this country and manufacturers' standards, safety codes, etc. have been developed on that basis. The National Electric Light Association has set up a national standard for lamp voltage of 115 volts with recognized departures of 110 and 120 volts. The National Electrical Code prescribes a maximum of 150 volts to ground for such service. The statement of the proportion of lamp sales among the various voltage classes given in Chap. IV indicates the prevalence of 115 volts as the service standard. The sale of 120-volt lamps is nearly as large but this may possibly be discounted somewhat by the use of such lamps on 115-volt systems by some companies. Household appliances and small single-phase motors are quite generally rated at 110 or 115 volts and are ordinarily well adapted for service up to 120 volts without undue shortening of their life or impairing their operation. The use of double voltage, *i.e.*, 230 volts has been tried and no doubt has certain

advantages but has never attained much popularity, as is indicated by the small percentage of lamp sales at those voltages. This is probably due to the fact that the lower voltages are so well established and also that 230-volt lamps are less efficient

Within the 110 to 120-volt range, the higher voltages would be the most advantageous from the standpoint of secondary service only. For a given load, line currents, and hence line losses, and voltage drops decrease as the voltage increases, allowing larger loads to be carried or longer lines to be used. The customer is likely to be better satisfied since his lamps burn brighter, his appliances heat faster, and occasional subnormal voltage conditions are less noticeable. However, when the system as a whole is considered, a lower or intermediate voltage may be of greater advantage. Motors are, in general, rated at 220 or 440 volts and standard distribution transformers at even ratios (10 to 1, 20 to 1, etc). Where both power and light are carried on the same lines, as is nearly always the case, the voltage on the lines must be satisfactory for both. If the lamp voltage standard is 120 volts, the corresponding 240 volts will be rather high for motors, especially if the 120 is the average voltage, and the maximum may run as high as 125 volts or 250 volts for motors. Even when power and light are carried on separate lines, it is often inconvenient to regulate the substation bus and the different lines to two different voltages. If different primary voltages are carried on lines and busses, the possibilities for emergency throwover are also reduced. The 115-volt standard, in general, offers a satisfactorily high voltage for lighting service and still gives a power voltage not too high for 220-volt motors, *i.e.*, 230 volts with a probable maximum of 240 volts.

A further discussion of these voltages in connection with combined secondaries for light and power will be found below.

Voltage for general service polyphase motors and large single-phase motors are quite generally standardized at 220 and 440 volts with guarantee of satisfactory operation at full load at + or − 10 per cent from rated voltage (but not necessarily with rated characteristics under such conditions). There are also standards of 550 and 2,300 volts but these are more often used for special purposes than for general service motors on the ordinary distribution systems. The choice between 220 and 440 volts generally depends considerably on the size of the load. For small loads, say 100 kw. or less, 220-volt service is generally

quite satisfactory, and has the advantage inherent in lower voltage of greater safety in handling, lower insulation, etc. For larger power loads, however, 440 volts is often of considerable advantage in spite of the increased difficulties in handling it, due to the lower line losses and smaller voltage drops, especially where the service wiring is somewhat extensive.

In general, it may be said that the use of one standard for secondary voltage on the whole system, instead of several, is very desirable from the point of view of standardization of equipment and operating practice and the reduction in confusion in both engineering and commercial departments. In establishing a definite standard for a system, the point at which the voltage is to be measured must also be defined since all customers cannot be served with the same voltage. The standard should be fixed as either the maximum, minimum, or average and whether it is voltage on secondary mains, customer's meter, or at the lamps. It is sometimes better to establish a range between certain minimum and maximum values, such as 112 to 120 volts, as the service standard rather than a single nominal value. The customer's meter is suggested as a convenient point since usually the customer is responsible for his own wiring beyond that point (to the outlets) and the drop in that wiring may vary considerably with different customers.

Combined Secondaries for Light and Power.—Wherever a load consisting of both single-phase lighting and polyphase power is to be served, either at individual customers or distributed over an area, there exists the possibility of handling the two separately as to transformers, secondaries, service wiring, etc., or of using a combined or common circuit on which both may be carried. The chief advantage in the use of separate circuits lies in the fact that large fluctuations in load, and especially motor-starting currents on the polyphase power system, are confined in their effects largely to that system. They do not materially affect the voltage on the single-phase system where close regulations is usually of more importance, unless of sufficient magnitude to cause disturbances in the primary voltage. The advantage of the combined system lies in the fact that the total number of conductors is reduced and also in some cases, the total cross-sectional area, since advantage may be taken of possible diversity between the two types of load, both as to time of operation and also phase angle. Where the single-phase load is equally

balanced on all the phases, some advantage in copper efficiency may also be gained.

No exact criterion can be set down as to where the combined circuit should or should not be used. It does not depend so much on the amount of either type of load as on the question of whether, in the particular case, the advantages are really to be found and in great enough degree to offset the accompanying disadvantages, of which there are some, as will be seen from the following discussion. Whether satisfactory service to both types of load can be rendered from the combined secondary, considering especially the effect on lighting of such dips in voltage as may be caused by fluctuations in the power load and motor-starting currents, will depend on the relative size of the transformers and of the largest motor connected. Where conditions are such that objectionable dips cannot be avoided without resort to excess capacity in transformers and secondary mains to prevent it, combined secondaries should as a rule not be considered. This usually precludes their use in districts of light or medium load density, since the starting currents of such three-phase motors as may occur in those districts will usually be large in comparison with the normal economical size of the lighting transformers. In heavily loaded districts, the reverse is usually true and here combined secondaries may often be used to advantage. The same is true of individual loads such as apartment houses where the power load is likely to be not over 20 or 25 per cent of the lighting load, with no very large motors.

Where the combined secondary is to be used, there are several possible circuits which may be employed, each having certain marked advantages and disadvantages. It cannot be said that any circuit has yet been proposed which can be generally accepted as ideal. The most commonly used will be discussed below:

Three-phase, Four-wire, Y-connected Secondary.—The type of three-phase secondary which is best adapted for use on secondary networks, as far as the design of the distribution system alone is concerned, is the Y-connected four-wire system illustrated in Fig. 60. On this system, single-phase load is balanced on the three phases by being connected between any phase-wire and the grounded neutral, balancing being done either in the individual service, if it is a four-wire service, or by balancing two-wire services on the mains. Three-phase load is connected to the three phase-wires. In this way, a virtual balance of load may be main-

tained all along the secondary; practically equal currents occur in all three phase-wires, and transformer capacity to feed the secondary is balanced on the three phases. (Usually banks of three similar single-phase transformers connected from phase to neutral are used, but three-phase transformers with the neutral point brought out may also be employed.) Balanced voltage is therefore maintained along the secondary.

From the standpoint of network operation the fact that the load is balanced on the three phases on the secondary is important. This precludes the necessity of balancing transformer installations or sub-areas on the primary feeder as is necessary with the delta-connected system. One continuous secondary

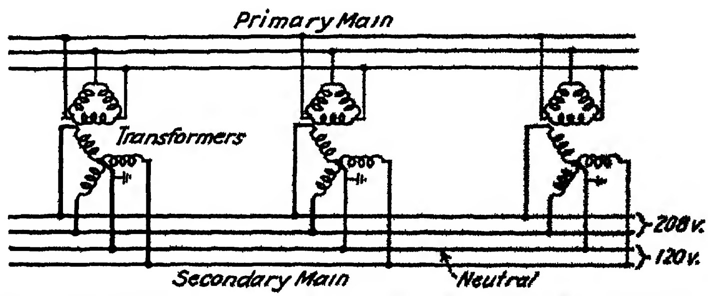

Fig. 60.—Combined secondaries—three-phase, four-wire, Y-connected.

can be laid down in the area to be served and there is no further necessity for redividing the area as the load increases, in order to maintain balance.

The outstanding disadvantage of this plan lies in the odd ratio existing between the voltages used for single-phase and for three-phase service. The ordinary standard for this ratio is 2, but with this type of secondary, the ratio must be $\sqrt{3}$ or 1.73. That is, if the voltage to neutral is 110 volts (for single phase), the voltage between phases is 190 volts (for three-phase). Similarly, if the phase-to-neutral voltage is 115 volts, the phase-to-phase voltage is 199, and if it is 120 volts, the phase-to-phase voltage is 208 volts. A standard for lamp voltage has been established (National Electric Light Association) at 115 volts with accepted departures of 110 and 120 volts. The ordinary standard for three-phase motors is 220 volts. It is apparent, therefore, that if the 115-volt standard is used, motor voltage will be decidedly substandard—very nearly 10 per cent low—and even if the highest

accepted departure 120 volts is adopted, the motor voltage is still over 5 per cent below standard. It might be possible to raise the voltage to such a point that the phase-to-phase voltage would be 216 to 220 volts, but in this case the voltage for lamps and appliances would rise to 125 to 127 volts. This is much too high for present standard heating appliances and would necessitate use of appliances and lamps designed for that voltage—120 volts is about as high as should be considered for the present line of appliances. The choice of 115 or 120 volts for the single-phase voltage is probably more practicable than either a higher or lower voltage, if this system is to be used.

With 115 or 120 volts from phase to neutral, the voltage supplied to three-phase motors will be from 5 to 10 per cent below that for which they were designed. The practicability of using such a system depends, in general, on two facts:

1 Standard motors are guaranteed by the manufacturer "to operate successfully at rated load and frequency with voltage not more than 10 per cent above or below name-plate rating, but not necessarily in accordance with the standards established for operation at normal rating."[1]

2. In practice, a majority of loads employ motors of larger rating than the actual load carried. At reduced load, a standard motor will operate at practically as good characteristics at reduced voltages as it shows at rated load and rated voltage.

The above conditions allow a combined secondary of this kind to be established in a district formerly served by separate secondaries and where 220-volt motors are prevalent. It is claimed by those who have done so that the substandard voltage gives rise to few complaints. Since normal voltages regulation on such a secondary will naturally be small, motors even at full load will operate satisfactorily within their 10 per cent guaranteed voltage range, while in most cases, the underloaded condition of the motors allows them to operate with at least as good characteristics as at full voltage. In the cases where full voltage is necessary, this may be secured by the use of autotransformers on the services but it is claimed that such cases have proved to be very few in practice.

Table V shows a comparison of characteristics of a typical standard 220-volt, three-phase, squirrel-cage, induction motor at 208 and 199 volts.

[1] N.E.M.A. Standard.

TABLE V.—COMPARATIVE CHARACTERISTICS OF THREE-PHASE INDUCTION MOTOR[1]

Values given in percentage of values at 220 volts

	208 Volts		199 Volts	
	100 per cent full load, percentage	50 to 60 per cent load, percentage	100 per cent full load, percentage	50 to 60 per cent load, percentage
Speed	99 7	99 85	99.4	99 7
Power factor	100 5	102.3	101	104
Efficiency	99 5	100.5	99	101
Current	105 2	103.0	110.3	106
Pull-out torque	89	89	81	81

The introduction of a 200-volt standard motor has been seriously considered and there is a good probability that this will be done if the use of 199- or 208-volt systems becomes at all general. The tendency will be for customers to buy motors rated at their service voltage regardless of whether or not a motor of higher voltage rating would serve the purpose.

The above table is taken from data[1] given by H. Richter in a paper on "Combined Light and Power Systems." This paper contains a quite complete discussion of the various possible voltages for this type of secondary from the manufacturers' point of view. In spite of the apparent advantages of this system and its practicability as demonstrated by several installations already made in large cities, there are many who seriously question the advisability of its general adoption. Probably the chief reason is that on a system where 220-volt service has been supplied at good voltage regulation, the reduction to 199 or 208 volts appears too much like a reduction in quality of service. The range in voltage allowed by the manufacturers' guarantee has been a safety factor, preventing some complaints in case of temporary drops in voltage which may occur due to operating troubles, etc. on the system. Also, it has been the policy of operating companies, in general, to discourage overmotoring on account of its effect on power factor, and it appears inconsistent to depend on it for satisfactory operation at reduced voltage. It is claimed that the introduction of an additional standard line of 200-volt

[1] RICHTER, H., "Combined Light and Power Systems," *Jour.*, A.I.E.E. Vol. 46, 1437.

motors would place an unwarranted expense on the industry, especially since the load carried on such secondaries will probably remain a small proportion of total load. In most systems there will be a large territory served at standard voltages in addition to the areas which would be served by these combined secondaries. Considerable confusion might arise from the use of different voltage standards in the two territories since customers moving from one to the other might find either their lamps and appliances or their motors or both not as well suited. A great many systems use the 115-volt standard for lamps but the 120/-208 volt combined secondary seems to be the most favored (208 being nearer the 220-volt motor standard). It is felt by many that a satisfactory combined secondary system, using the network principle where warranted, may be installed, using one of the schemes to be described below, without resorting to the introduction of unstandard voltages, and although perhaps not as ideal as the Y-connected, four-wire system from the standpoint of the distribution system alone, will be more satisfactory from a commercial standpoint. At present, no general agreement has been reached on this question. Several Y-connected systems have been put into operation as have also systems using the other schemes. It seems probable that all of them will be used to some extent for some time to come and that no universal standard can be expected until it naturally works itself out.

Before leaving the Y-connected system, a few more points in connection with it should be noted. On three-wire, single-phase service, metering cannot be done with the ordinary three-wire, single-phase meter on account of the phase angle between the two (115-volt) single-phase voltages. Two single-phase meters, a polyphase meter, or a meter specially designed for the purpose must be used. This may be avoided by using heavier two-wire services for single-phase loads. On three-phase services, the metering problem is somewhat simpler than on the delta-connected secondary since the load is balanced.

Another point of interest is that the line losses and voltage drops for motor load are increased due to the reduction in voltage. At 199 volts, for example, the motor current is increased approximately 10 per cent at full load, hence the line loss is increased 21 per cent, and the voltage drop 21 per cent for the same load and the same size of conductor. Similarly, on a three-wire, single-phase service, even though the load is balanced, the third

wire carries as much current as the other two (due to the phase angle between voltages) instead of no current as with the ordinary three-wire, single-phase service. Hence, power loss on the service wires (and interior service wiring if the system is extended through the building) is increased 50 per cent and voltage drop is also increased. These factors may or may not be of considerable importance, according to conditions, but they should be recognized.

Three-phase, Four-wire, Delta-connected Secondary.—This plan, see Fig. 61, consists essentially of a three-phase secondary with all the single-phase load carried between phase-wires on one phase, the midpoint of the transformers on that phase being brought out for the grounded mid-wire of the single-phase secondary.

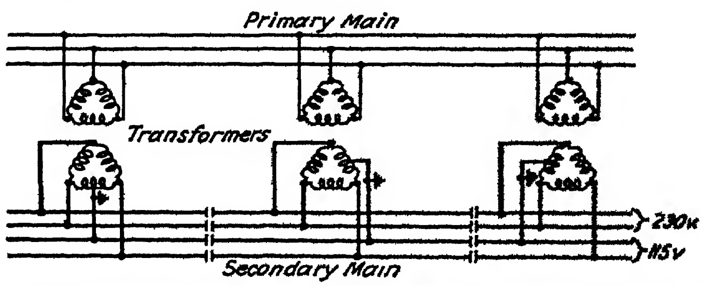

Fig. 61—Combined secondaries—three-phase, four-wire, delta-connected.

Transformers serving this secondary are, of course, connected in delta on the secondary side and may be Y or delta on the primary but usually are delta. The transformer across one phase must be larger than those across the other two in order to accomodate the single-phase load. The division of load on such a bank of transformers is discussed in Chap. IX.

This scheme has the advantage of offering the usual standard ratio between three-phase and single-phase voltages, *i.e.*, 115 volts for lighting and 230 volts for power.

Its chief disadvantage lies in the fact that on each section of secondary the single-phase load is entirely unbalanced on the phases, being all carried on one phase. Balancing of the load on the primary feeder must be done by balancing transformer installations, the single-phase load being carried on one phase on one, and on another phase on another, etc. This balancing is done in one of two ways, either by balancing alternate transformer installations, keeping their secondaries separate, or by

dividing the total area into three parts and carrying the single-phase load on a different phase in each part, the load being balanced as nearly as possible by the division of the areas. In the latter plan, transformer secondaries may be tied together into a *secondary bank* or *secondary network* in each of the phase-areas. Since the grounded point is on a different phase in each area (or on each transformer installation if the first method is used), adjacent secondaries cannot be tied together directly They can be tied inductively through a one-to-one transformer, or similar device, if desired. With the phase-area plan, however, such a tie will usually be superfluous. Its purpose is to provide for equalization of load and voltage between areas and emergency

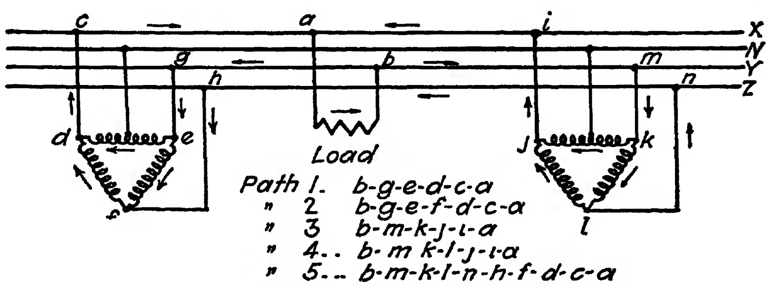

FIG. 62.—Division of load on delta-connected network

feed through in case of trouble but it will ordinarily be found more practicable to design each phase area as an independent network with sufficient reserve capacity for its own needs.

The unbalance in load on transformers and secondaries introduces an unbalance in service voltage which is not encountered with the Y-connected system. This will ordinarily not be serious enough to cause serious difficulty but cases have been experienced where the unbalance has been enough to affect the operation of some of the older types of motors which were carrying rather heavy loads.

The delta-connected system, if applied to a *secondary bank* or a *secondary network* with *closed-delta* transformer banks, introduces certain difficulties in design and operation due to the multiple paths through the transformers which may be taken by any load. Figure 62 illustrates this. The load indicated may be served by any of the various paths noted and will be divided among them in inverse proportion to their impedances. This fact results in making the distribution of load among the various

transformers on the phase carrying the single-phase load and also on the other phases very hard to predetermine mathematically, especially if transformers of various sizes are used. Also a change in size for any transformer entirely upsets the previous condition. A transformer replacing a smaller size on account of overload may find itself picking up still more of the load and relieving the other transformers more than was anticipated.

This difficulty may be avoided by use of open-delta transformer banks if the conditions of loading are such as to make them feasible. In Chap. IX on "Transformers" the application of open-delta transformer banks to combined loads is discussed. It is sufficient to say here that where the single-phase load is at least as large in kilovolt-amperes as the three-phase, an open-delta transformer bank will give a better balanced voltage and more efficient use of transformer capacity under the combined load than a closed-delta bank. The open delta has the further advantage of avoiding the complication of circuits mentioned above. All the single-phase load is carried on the transformer connected across that phase and none can circulate through the other phases.

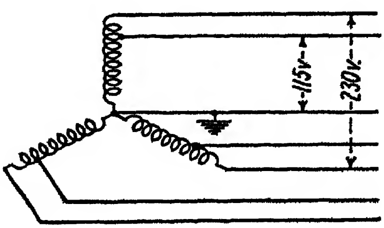

FIG. 63—Combined secondaries—three-phase, seven-wire, Y-connected.

Three-phase, Seven-wire, Y-connected Secondary.—The connection shown in Fig. 63 is used in at least one city for network distribution. Both three-phase and single-phase loads are carried on the same transformer banks thus reducing the number of transformer units and gaining some advantage possibly from diversity between them, in reducing the total transformer capacity which would be necessary with separate installations. The secondary mains are separate, however, consisting essentially of a system of three-wire, three-phase mains at 230 volts between phases, for power loads, and a system of four-wire, Y-connected, three-phase mains with 115 volts between phase-wires and grounded neutral on which the single-phase load is balanced among the three phases. Transformers are connected in Y and give 133 volts to neutral (for the 230-volt power mains) with taps brought out to give 115 volts to neutral for the lighting mains. The system has the advantage of supplying standard voltages

but has the disadvantage of being a combined system only in so far as the transformers are concerned, the secondary mains comprising two separate systems and one of these a four-wire, three-phase system for carrying single-phase loads only. Balancing small loads on such a system is somewhat more difficult than on a three-wire single-phase system and separate services must be used for all three-phase loads.

Two-phase, Five-wire Secondary.—The two-phase, five-wire secondary indicated in Fig. 64 offers a satisfactory system as far as voltages and copper efficiency is concerned but is applicable only where two-phase motors are prevalent. For such cases it offers standard voltages for both light and power. Three-phase primaries may be used with Scott-connected transformers. A detailed study of this plan is presented by P. H. Chase.[1] He shows little choice in cost between three-phase and two-phase systems employing the same type of primary. Considering the cost of changing over from one type to the other there seems to be little advantage to be gained in changing either a two-phase system to three-phase or *vice versa* in a district where either is well established.

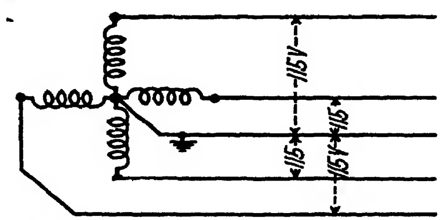

FIG. 64.—Combined secondaries—two-phase, five-wire.

Size of Secondary Mains.—The proper size for secondary mains offers quite a field for economic study, as a rule. Something has been said already about the limitations of size in secondary networks in order to provide proper distribution of load among transformers, burning off of faults, etc. For the ordinary radial secondary or secondary bank (overhead) the following conditions govern the choice of size of secondary wire:

1. *Mechanical Strength.*—No. 6 weatherproof wire is about the smallest practicable size in heavy-loading districts,[2] and, for load densities of any appreciable amount, it is doubtful if a smaller size is often economical, even if this were not the case. No. 8, if used, should be carried only in short spans. Wires larger than No. 00 are somewhat difficult to handle on overhead construction for secondaries, but No. 0000 and even

[1] "Two-phase, Five-wire Distribution," *Jour.*, A.I E.E , Vol. 44, 8, August, 1925.

[2] National Electrical Safety Code.

larger, up to 500 M. cir. mils, are practicable and economical under certain conditions.

2. *Voltage Drop.*—The secondaries must be large enough to give voltage at the extreme service within the prescribed limits and also to provide against voltage dips due to motor-starting currents, etc. This is especially important where possible transformer locations are limited.

3. *Economical Considerations.*—For any load a study of annual costs will indicate a most economical size of secondary, but the study must also include consideration of transformer sizes and spacing if any variation of these is possible.

CHAPTER VIII

STREET-LIGHTING CIRCUITS

In general, street-lighting circuits may be divided into the following classes:

1. Direct-current arc circuits.
2. Alternating-current series circuits.
3. Alternating-current multiple circuits.

Alternating-current arc circuits have been used to some extent but are now obsolete.

Direct-current Arc Circuits.—Direct-current arc circuits were formerly used quite extensively but with the development of the alternating-current incandescent system, the direct-current systems have been quite largely superseded. Their chief use at present is probably in downtown districts of some cities for high intensity lighting, the circuits all being fed from substations. They are commonly supplied from mercury-arc rectifiers.

Alternating-current Series Circuits.—The most commonly used circuit for street lighting is the series circuit fed by a constant current transformer or regulator. The series circuit offers the advantage of maintaining uniform intensity of illumination (for lamps of the same size) at a fairly large number of locations spread out over a large territory and using only a two-wire circuit of comparatively small wire. The values of current used are 4, 5.5, 6.6, or 7.5 amp. with the greater majority using 6.6 amp. Two types of lamps are used on these circuits. Those of lower intensity, up to 4,000 lumens, are operated directly on the 6.6-

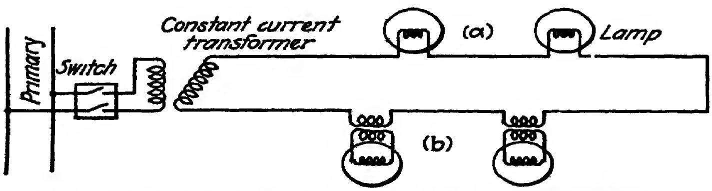

FIG. 65.—Diagram of alternating-current series street-lighting circuit: (*a*) Lamps in main circuit; (*b*) High-current lamps with transformers.

amp. circuit, Fig. 65(*a*). A simple type of cutout serves to shunt out the lamp and maintain operation of the circuit in case a lamp burns out. The higher intensity lamps, 6,000 lumens or more, are usually operated at 15 or 20 amp. being supplied from the 6.6-amp. circuit through small transformers, Fig. 65(*b*). In case of a lamp burnout, no interruption to the circuit is caused, the transformer merely continuing to operate with its secondary circuit open (or a cutout may be used).

The 20-amp. series circuit has had some use and has certain advantages. Where the lamps to be used are all in the 20-amp. range of sizes, the 20-amp. circuit allows the elimination of the small transformers at each lamp. The voltage of the circuit as a whole is also reduced to about one-third that for a 6.6-amp. circuit with the same load, thereby reducing the insulation necessary (especially applicable in reducing the cost of cables). On the other hand, the larger current increases the line losses about nine times. Also the losses due to induction in sheath and armor when single-conductor metallic sheathed and armored cables are used, increases in still greater proportion. These may be reduced by use of non-metallic sheathed cables, however, where such are found practicable. Other disadvantages are the necessity of using film cutouts to remove burned-out lamps from the circuit, and higher voltage up the pole (underground ornamental systems). On overhead circuits, the National Electrical Safety Code requires a considerably higher grade of construction for a 20-amp. circuit than for a 6.6-amp. where it crosses or conflicts with communication circuits. The question is quite largely an economic one, whether the 20-amp. circuit will be more economical, everything considered, than the lower current circuit, and it can only be answered by a study of the particular case.[1]

Originally street-lighting circuits were run from substations where the transformer was located and where they could be turned on or off by a very simple switching operation without any intricate control apparatus. With the increase in size of systems and with the more widespread use of street lighting, especially along country highways, etc, there has come the necessity for feeding these circuits at other points than centrally located substations and, of course, also the necessity for turning the circuit on and

[1] BUTLER, HENRY E., "Features of 20-ampere, Alternating-current Series Street-lighting Circuits," *General Electric Review*, Vol. 31, p. 555, October, 1928.

off by some automatic or remotely controlled device. Several methods have been used for this. In each one the constant-current transformer may be mounted at a point remote from the substation or control point and, except with the separate primary feed, may be fed from any distribution circuit in the neighborhood. Supply to the transformer passes through an oil switch which is closed and opened by the controlling device. The chief methods used for this control are described briefly below.

1. *Time Clock.*—The switch is controlled by a time clock set to operate it on a predetermined schedule. This scheme has the advantage of being applicable to any point on the system no matter how remote, provided the primary supply is available. Its disadvantage lies in the necessity for winding and setting

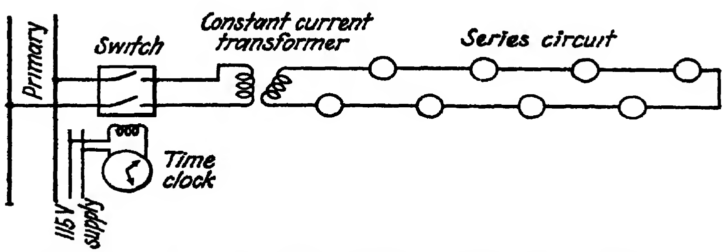

FIG 66.—Diagram of time-clock control for series circuit.

the clock periodically and the inherent disadvantage in depending on a more or less delicate mechanism (a clock) for use where conditions are likely to be very adverse, such as outdoor installations operating under all sort of weather conditions, inexpert and irregular attention, etc.

Figure 66 shows a diagram of such an installation.

2. *Series Relay.*—In this scheme, a relay is inserted in series with some other series street-lighting circuit which is operated directly from the substation or control point. When this series circuit is turned on the relay actuates the oil switch, which closes and thereby turns on the second circuit. This can be extended by operating several auxiliary circuits by one main circuit or by operating another auxiliary circuit off the first auxiliary circuit, etc.

Figure 67 shows a diagram of this scheme. Its advantage lies in a relatively simple control through the small series relay. It can be used, however, only where a directly controlled series circuit is available for operating the relay, *i.e.*, a comparatively

short distance from the control point, or where several circuits may be connected in cascade, beginning at the control point. It has the further disadvantage of allowing an interruption in the control circuit to interrupt all the other circuits which it controls either directly or indirectly.

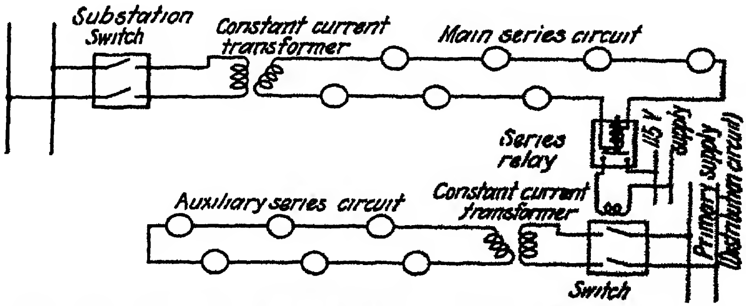

Fig. 67.—Diagram of series-relay control for series circuit.

3. *Pilot Wire.*—The various circuits may be turned on by relays actuated by a pilot-wire system running from the central control point to each one. Several different variations of this plan have been used, *i.e.*, continuous current in the pilot wire, single impulses for turning on and turning off, and combinations of

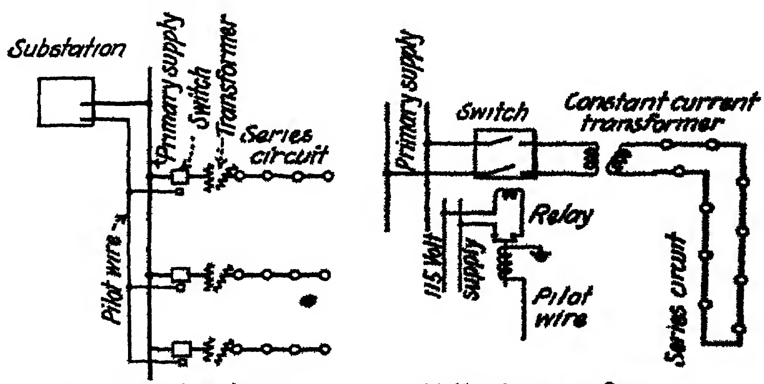

Fig. 68.—Diagram of pilot-wire control for series circuit.

impulses to control different circuits at different times (midnight circuits, all-night circuits, etc.). One system uses power from the neighboring 115-volt secondaries for actuating the pilot-wire circuit, and where such a circuit is too long or controls too many installations to operate properly with the power available, other

pilot circuits are added in cascade, controlled by the master circuit.

Figure 68 illustrates the pilot-wire method.

4. *Carrier Current.*—The use of auxiliary circuits (pilot wire, etc) is avoided by sending out currents over the power-supply

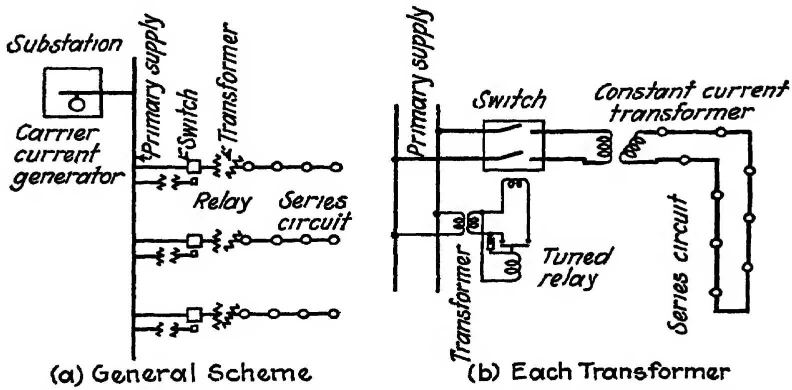

FIG 69 —Diagram of carrier-current control for series circuit.

circuits at frequencies different from that of the power supply. Relays at each street-circuit transformer installation are tuned to respond to these particular frequencies, usually one for opening and a different one for closing, and actuate the switches accordingly. Figure 69 diagrams this scheme.

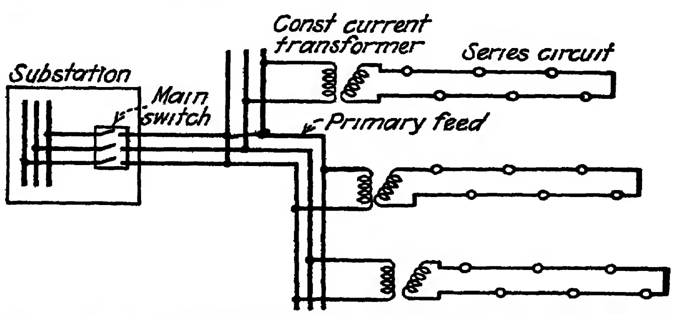

FIG. 70.—Diagram of independent primary feed for series circuits.

5. *Independent Primary Feed.*—In this, a separate primary feed is run from the substation or control point, which feeds only street-circuit transformer installations and is entirely independent of other distribution circuits. It may be extended to any reasonable distance so that the street-lighting transformers may be arranged as best suited to the load. The advantages are a direct

and simultaneous control of all series circuits and multiple feed at primary voltage (as compared with direct series feed for all circuits). It is probably the most rugged and dependable of any of the systems of remote control. Its disadvantage lies, of course, in the extra line wires and substation apparatus and hence somewhat greater cost than some of the other methods (time-clock control, for example).

Figure 70 shows a diagram of this plan.

Layout.—The series circuit may be arranged with the two wires of the circuit running in parallel to each lamp, or with the open

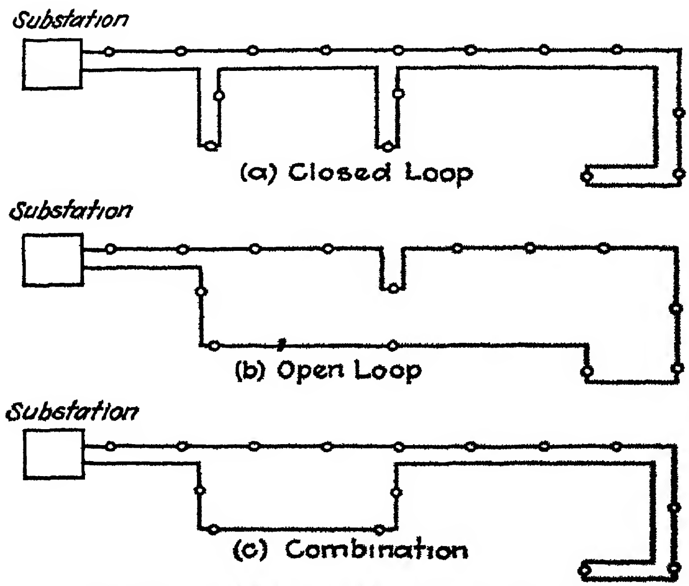

Fig. 71.—Diagram of series circuit layout.

loop, *i.e.*, one wire running out by one route and returning by another, or a combination of the two. As a matter of economy, the open loop is usually of advantage, but for locating trouble on the circuit the closed-loop or parallel-wire arrangement is preferable since any part of the circuit can be cut off and isolated by a short jumper between wires. Short sections of open loop as branches from a main closed-loop circuit may sometimesbe used to advantage and are preferable to the complete open-loop plan.

Figure 71 shows the three plans in diagram.

Multiple Circuits.—The multiple or constant-voltage circuit has been used to some extent in the past but its use has been more

or less limited by the difficulty of obtaining a simple, reliable method of turning the lamps on and off in large numbers from a central control point. Several solutions for this problem have been offered and in recent years the use of multiple circuits has been considerably stimulated. Multiple circuits have probably been more often employed for either incidental groups of a few lights, where constant potential distribution circuits were available for their supply, or for downtown "white-way" lighting with comparatively large capacity per lamp location, rather than for general street-lighting systems. With the development of methods for remote control, however, their general use is possible and has been introduced in some cities.

The advantages of multiple circuits lie in the fact that the street lighting may, if desired, be fed from the same transformers as the local distribution load by the addition of proper wiring. While little advantage in reducing transformer capacity due to diversity can be claimed, since the street-lighting load will nearly always be on at the time of peak-lighting load, this load can be handled quite simply as would any other load in the district. The constant-current transformers with their relatively poor efficiency and poor power factor (at partial load) are eliminated and the cost for transformer capacity reduced. The circuits are at much lower voltage (115 volts) than the ordinary series circuit and troubles and possibilities of interruption to service are thereby reduced.

On the other hand, if the multiple circuit is of any considerable length, uniformity of illumination is difficult to accomplish, since the voltage decreases with the distance from the transformer and unless this is compensated for in some way, illumination from equal-sized lamps will correspondingly decrease. The multiple lamp is a somewhat less efficient unit than the higher current series lamp, especially in the larger sizes, and has shorter life. In one city these disadvantages have been overcome by the use of series-type lamps fed by small individual autotransformers built into the unit, which are connected in multiple across the 115-volt circuit. Differences in voltage are compensated for by taps in the transformer.

The simple multiple circuit is illustrated in Fig. 72.

As has been mentioned, one of the chief difficulties in connection with the use of multiple circuits is the necessity of some form of remote control. This is a serious disadvantage as

compared with the simple series circuit controlled at a substation, on account of the more or less complicated devices required and their large number, since multiple lamps cannot be controlled in large groups. With large units, each lamp must be individually provided with control equipment. With smaller units, several may be grouped on one circuit but the number is limited

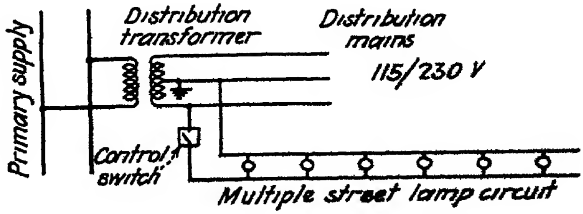

FIG. 72.—Diagram of multiple circuit.

by the voltage drop in the wires. The several methods used for actuating the control switch are as follows:

1. *Hand Method.*—This is, of course, the simplest, but also the most unsatisfactory, requiring individual attention at each switch at least twice each day. It is out of the question on a system of any appreciable size.

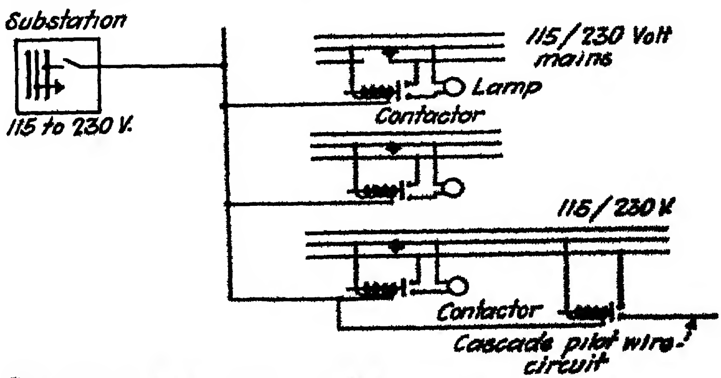

FIG. 73.—Diagram of pilot-wire control for multiple circuits.

2. *Time-clock Method.*—This has the same disadvantages as noted under similar control for series circuits, *i.e.*, the clocks are comparatively delicate mechanisms and require a considerable amount of attention to keep running properly. In addition, they are likely to make the system quite expensive in the large number required for control of individual lamps or small groups on the multiple system.

3 *Relay in Series with a Separate Control Circuit,* Fig. 73.—Several control circuits may be connected in cascade where the energy required for operating the switches is too great for one circuit. A variation of this scheme is the use of a series relay connected in an operating series street-lighting circuit to actuate the switch of an auxiliary multiple circuit.

4 *Carrier Current.*—Relays employing tuned circuits which respond only to currents of the particular frequencies to which

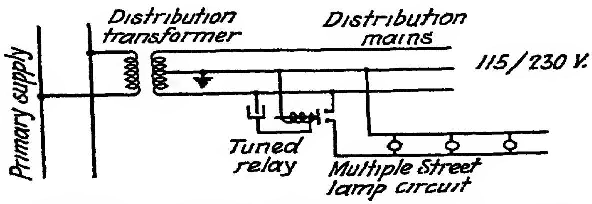

FIG 74.—Diagram of carrier-current control for multiple circuits.

they are tuned are used to operate the control switches. Currents of the proper frequencies (usually one for opening and another for closing) are sent out from the control point over the power wires, superimposed on the normal frequency current. A special generator is used for producing these control currents, see Fig. 74. This scheme eliminates the special wires necessary with the pilot-wire control but the apparatus is somewhat more delicate.

CHAPTER IX

TRANSFORMERS

The connecting link between primary distribution and secondary distribution, as they have been discussed in previous chapters, is the transformer which serves to step down the relatively high primary voltage to the secondary or utilization voltage. Some consideration has already been given the transformer in Chap. VII, "Secondary Distribution," since the design of the secondary system naturally involves the study of the proper use of transformers in their relation to the secondary wires. There are, however, a number of points regarding transformers specifically which should be given further attention and will be taken up in this chapter.

It is not within the province of this work to go into the details of transformer design to any extent. Not that the design is not of considerable interest to the distribution engineer, but a distribution transformer is a piece of apparatus which is usually used under conditions where it is unattended, subject to infrequent inspection or none at all, and must endure all sorts of weather variations —heat, cold, rain, lightning, etc. In it there is lost from 3 to 5 per cent (or sometimes more) of all the energy transmitted. Hence, it is important that it is properly designed to operate continuously and efficiently. The study of transformer design is a specialized subject, however, and the distribution engineer's chief concern is with its characteristics as affecting its use on the system. It is from this viewpoint that transformers will be considered here.

Elementary Theory.—The two-circuit transformer consists essentially of two separate coils of wire wound on the same iron core and insulated from each other, Fig. 75.

When the terminals of one coil, the primary coil, are connected to a source of alternating potential, the secondary coil being open, a small current will flow through the coil. This current is called the "exciting current of the transformer." It is made up of two components. One of these, *the magnetizing current*, is that

resulting from the application of voltage across the inductive circuit of the coil, and lags 90 deg. behind the applied voltage. This current produces an alternating magnetic flux in the iron core (in phase with itself) which interlinks with both the primary and secondary coil inducing an electromotive force in each. This electromotive force lagging 90 deg. behind the flux is hence 180 deg. out of phase with the applied voltage and, in the primary coil, becomes a counter-electromotive force opposing the applied voltage. The counter-electromotive force is very nearly equal to the applied electromotive force, there being enough difference to cause the necessary exciting current to flow.

The other component of the exciting current is that due to the core loss in the iron core. This is a real power loss, hence the

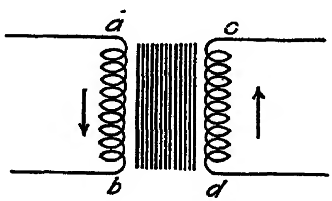

Fig. 75.—Elementary diagram of transformer

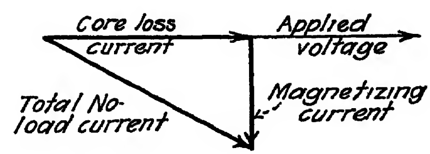

Fig 76.—No load or exciting current of transformer.

current is in phase with the applied voltage. The vector sum of the magnetizing current and the core loss current is the exciting or no-load current of the transformer as shown in Fig. 76. It is ordinarily small compared with the full-load current, of course.

The interlinkage of the magnetic flux in the core with the secondary coil also produces an electromotive force in it. If the secondary coil is wound in the same direction around the core as the primary coil, this electromotive force is in opposite direction to the applied voltage in the primary, *i.e.*, if the applied voltage is from *a* to *b*, Fig. 75, at any instant, the secondary electromotive force would be generated from *d* to *c* or so that if the secondary circuit were closed, current would flow from *c* to *d* through the exterior circuit and *d* to *c* through the coil. If the secondary coil is wound in the opposite direction around the core, the reverse is true, the electromotive force being generated from *c* to *d*, and current in the exterior circuit being from *d* to *c*. This factor governs the polarity of the transformer which will be discussed later.

If the terminals of the secondary coil are connected to an exterior circuit, such as a motor or a group of lamps, the potential across this circuit will cause current to flow as stated above. This current flowing through the secondary coil produces a magnetic flux which tends to demagnetize the core and reduce the effective impedance of the primary. This in turn allows more current to flow through the primary coil, sufficient to balance the magnetic flux due to the secondary current. This primary current is in the same phase relation to the primary applied voltage as the secondary current is to the secondary voltage.

The number of *ampere turns* in the primary and secondary coils must be equal (neglecting losses), hence the relation between primary current and secondary current is approximately inversely as the number of turns in the respective windings, *i.e.*

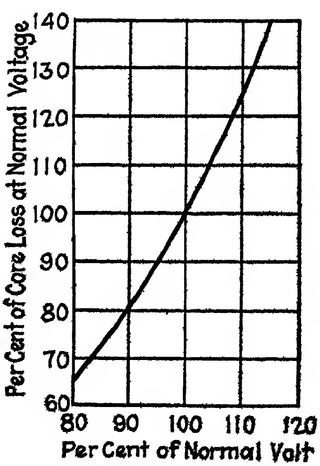

FIG. 77.—Variation of core loss with voltage.

$$I_p n_p = I_s n_s.$$

$$\frac{I_p}{I_s} = \frac{n_s}{n_p}.$$

Where I represents current, n the number of turns, and the subscript p refers to primary, and s to secondary.

The ratio between the number of turns is called the "transformer ratio." It is also approximately the ratio between the primary voltage and the voltage induced across the secondary, since the same voltage per turn exists in both windings, neglecting leakage.

For example, if the primary has twenty times as many turns as the secondary, the turn ratio is 20 and the primary voltage is approximately twenty times the secondary voltage (as 4,600/230).

Losses.—Energy losses in a transformer are chiefly of two kinds:

1. *Core loss* due to hysteresis and circulating currents induced in the core. This loss has practically a constant value for any transformer regardless of the load carried provided the voltage is constant; hence it is a 24-hr.-a-day load on the system. The core loss increases with increase in the applied voltage and is materially greater if the transformer is operated at a voltage which is any considerable amount above its rated voltage. Figure 77

shows the approximate variation of core loss with voltage for a typical case.

2. *Copper loss* due to the passage of load current through the resistance of the windings. This is an I^2R loss and hence varies with the square of the load current carried, being maximum at peak load and 0 at 0 load. The total copper loss experienced with any transformer therefore, depends entirely on the shape of the load curve. Copper loss is affected by the voltage applied only

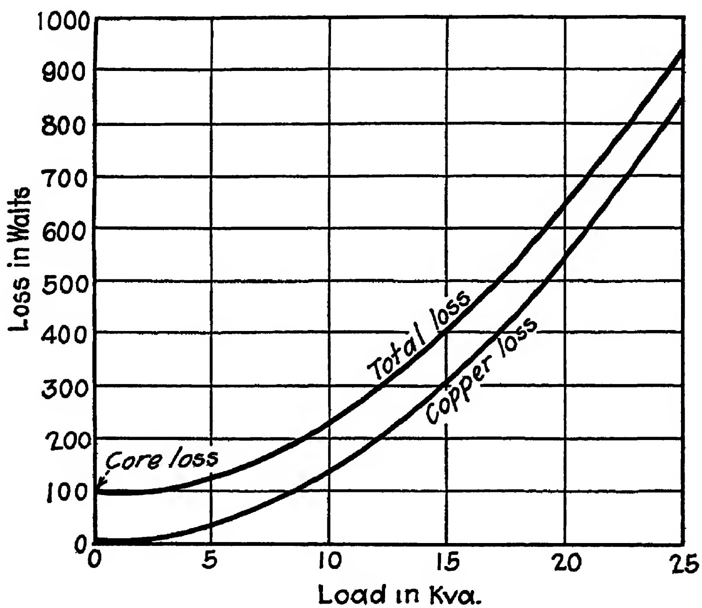

FIG. 78.—Losses in typical 15 kv-a. single-phase distribution transformer.

in so far as the load current is affected, *i.e.*, for the same kv-a,. the load current is inversely proportional to the voltage, hence the copper loss is inversely proportional to the square of the voltage.

The losses for a typical line of distribution transformers of various sizes are shown in Table VI. These vary somewhat with different makes of transformers, of course. Figure 78 shows how the variation of losses with load may be plotted graphically.

TABLE VI.—LOSSES OF TYPICAL LINE OF DISTRIBUTION TRANSFORMERS

Single-phase 4,600/2,300—230/115 Volt

Size	Core loss, watts	Copper loss, watts (full load)
1½	25	51
3	31	85
5	42	125
7½	54	170
10	67	213
15	88	306
25	119	470
37½	159	682
50	206	765
75	330	1,200
100	460	1,460
Three-phase 4600-460/230 volt		
5	70	125
7½	80	165
10	90	210
15	115	280
25	165	390
37½	215	600
50	250	780
75	430	1,000
100	500	1,115

Resistance, Reactance, Impedance.—In studying problems of voltage regulation, paralleling transformers, division of load between transformers, etc., it is essential to know their resistance and reactance. Since both primary and secondary coils have resistance and reactance, the values for each might be given separately. They are difficult to obtain in this form by test, however, and not of much use when obtained, since the whole transformer is usually considered as a part of either the primary or secondary circuit in computing voltage drops, losses, etc. That is, the voltage drop through a transformer cannot be given as so many volts but must be referred to either the primary voltage or the secondary voltage, making due allowance for the turn ratio. If given as a percentage, however, it may refer to either (and may be reduced to volts, if desired, by applying it to either primary or secondary voltage as the case may

be). Resistance, reactance, and impedance of a transformer are therefore usually quoted as percentages and refer to the transformer as a whole, including both primary and secondary coils. For example, a transformer is said to have 4 per cent reactance, etc.

The per cent *impedance* given for any transformer may be conveniently interpreted as follows: The percentage of the normal rated primary voltage which must be applied to the transformer to cause full rated load current to flow in the short-circuited secondary. That is,

$$E_z = I_p Z_p$$

where

E_z = applied voltage (to primary).
I_p = full rated load current (primary).
Z_p = equivalent impedance of transformer.

$$\text{Per cent impedance} = \frac{E_z}{E}.$$

Hence if the per cent impedance is given for any transformer, the equivalent impedance in ohms, referred to the primary current may be found as follows:

Let I_p = full-load primary current

$$= \frac{\text{transformer capacity in kilovolt-amperes} \times 1{,}000}{\text{rated primary voltage}} = \frac{W}{E_p}.$$

$$Z_p = \frac{E_z}{I_p} = \frac{\text{per cent impedance} \times E_p}{I_p \times (100)} = \frac{\text{per cent impedance} \times E_p}{\frac{W}{E_p} \times (100)}$$

$$= \frac{\text{per cent impedance} \times E_p^2}{W \times (100)} \text{ ohms.} \tag{1}$$

Similarly, referring to the secondary current of the transformer

$$Z_s = \frac{\text{per cent impedance} \times E_s}{I_s \times (100)} = \frac{\text{per cent impedance} \times E_s^2}{W \times (100)} \text{ ohms.} \tag{2}$$

Since

$$E_p = nE_s,$$

where n = transformer turn ratio,

$$\frac{Z_p}{Z_s} = \left(\frac{E_p}{E_s}\right)^2 = n^2. \tag{3}$$

• That is, the impedance in ohms referred to the primary current is equal to the square of the turn ratio times the impedance in ohms referred to the secondary current.

For a numerical example assume a 2,300/230-volt transformer with 5 per cent impedance given, the transformer capacity being 10 kv-a. The turn ratio is 10.

$$Z_p = \frac{5 \times 2{,}300^2}{10{,}000 \times 100} = 26.45 \text{ ohms}$$

$$Z_s = \frac{26.45}{10^2} = 0.2645 \text{ ohms.}$$

In problems pertaining to distribution, resistance and reactance are probably more often used than impedance. The same relation holds true among the three quantities as in any electrical circuit, *i.e.*,

$$Z^2 = R^2 + X^2.$$

whether the quantities are given in percentages, (per cent Z, per cent R, per cent X), in ohms referred to the primary side (Z_p, R_p, X_p), or in ohms referred to the secondary side (Z_s, R_s, X_s). If any two of the quantities are known, the third may then be computed.

For example, if

per cent Z = 4 per cent,
per cent R = 2 per cent,
per cent $X = \sqrt{16 - 4}$ = 3.46 per cent.

The reduction of either resistance or reactance, when given in percentages, to ohms, referred either to the primary or secondary side of the transformer, can be made by formulas similar to those given above for impedance, that is:

$$R_p = \frac{\text{per cent resistance} \times E_p^2}{W \times (100)} \text{ ohms.} \tag{4}$$

$$R_s = \frac{\text{per cent resistance} \times E_s^2}{W \times (100)} \text{ ohms} = \frac{R_p}{n^2}. \tag{5}$$

$$X_p = \frac{\text{per cent reactance} \times E_p^2}{W \times (100)} \text{ ohms.} \tag{6}$$

$$X_s = \frac{\text{per cent reactance} \times E_s^2}{W \times (100)} \text{ ohms} = \frac{X_p}{n^2}. \tag{7}$$

Since the copper loss of the transformer is the loss incurred by the passage of the current through the resistance of the wind-

ings, (neglecting eddy currents in the windings), if copper loss is given in watts, equivalent resistance may be computed from it (or *vice versa*).

Watts loss (full load) $= I_p^2 R_p = I_s^2 R_s$

Example.—10 kv-a 2,300/230-volt transformer, copper loss 215 watts at full load.

$$I_p = \frac{10{,}000}{2{,}300} = 4\ 35 \text{ amp}$$

$$R_p = \frac{215}{4\ 35^2} = 11\ 37 \text{ ohms}$$

$$R_s = 0\ 1137 \text{ ohms}$$

If the resistance of the primary and secondary windings are determined separately by direct test with direct current, the equivalent resistances may be computed as follows:

$$R_p = \text{resistance of primary winding} + n^2 \text{ (resistance of secondary winding).}$$

$$R_s = \frac{\text{resistance of primary winding}}{n^2} + \text{resistance of secondary winding}$$

Voltage Drop.—The quantities R and X, as determined above, may be used to determine the voltage drop through the transformer, employing any of the methods shown in Chap. X. The drop must be referred to either the primary or secondary side, using the proper values of R_p and X_p or R_s and X_s to correspond. With the approximate formula:

$$\text{Volts drop (primary side)} = I_{p_1} (R_p \cos\theta + X_p \sin\theta) \qquad (8)$$

where

I_{p_1} = any load current on primary—full load or otherwise

$\cos\theta$ = power factor.

$$\text{Volts drop (secondary side)} = I_{s_1} (R_s \cos\theta + X_s \sin\theta). \qquad (9)$$

$$\text{Per cent volts drop} = \frac{\text{volts drop (primary)}}{E_p} = \frac{\text{volts drop (secondary)}}{E_s} \qquad (10)$$

For Polyphase Transformers.—In dealing with polyphase transformers or transformer banks it is usually more convenient to use the quantities R, X, and Z as applying to phase-to-neutral rather than phase-to-phase circuits.

The formulæ given above were derived for single-phase conditions. If it is desired to use them on a three-phase transformer or a three-phase bank of single-phase transformers, the load across one phase (one-third the total) must be used, and the results thus obtained refer to the phase-to-phase condition. If phase-to-neutral characteristics are desired, however, they may be obtained by dividing the phase-to-phase characteristics by 3. This is evident when it is observed that R, X, and Z (in ohms) are proportional to the square of the applied voltage. Since the phase-to-neutral voltage is $1/\sqrt{3}$ times the phase-to-phase voltage, the ratio between phase-to-phase and phase-to neutral characteristics is, of course, 3 to 1. Expressed mathematically,

if W = total load on the three-phase installation (in watts),
E_p = phase-to-phase voltage.

Phase-to-phase.

$$R_p = \frac{\text{per cent resistance} \times E_p^2 \times 3}{W \times (100)} \text{ ohms.} \qquad (11)$$

$$X_p = \frac{\text{per cent reactance} \times E_p^2 \times 3}{W \times (100)} \text{ ohms.} \qquad (12)$$

$$Z_p = \frac{\text{per cent impedance} \times E_p^2 \times 3}{W \times (100)} \text{ ohms.} \qquad (13)$$

Phase-to-neutral.

$$R_p = \frac{\text{per cent resistance} \times E_p^2}{W \times (100)} \text{ ohms.} \qquad (14)$$

etc., *i.e.*, the same expressions as given for single phase but using total three-phase load for W.

Example.—25 kv-a. 4,600/230-volt, three-phase transformer per cent R = 1.86; per cent X = 3.13.

Phase-to-neutral $R_p = \dfrac{1.86 \times 4{,}600^2}{25 \times 1{,}000 \times 100} = 15.75$ ohms.

$$R_s = \frac{15.75}{20^2} = 0.0394 \text{ ohms.}$$

$$X_p = \frac{3.13 \times 4{,}600^2}{25 \times 1{,}000 \times 100} = 26.5 \text{ ohms.}$$

$$X_s = \frac{26.5}{20^2} = 0.0662 \text{ ohms.}$$

Transformer Connections.—A volume could be written about various transformer connections but here the discussion must be confined to those most ordinarily used in distribution practice:

1. *Single-phase, Two-wire, Fig.* 79.—Standard single-phase distribution transformers are generally designed with the secondary coil in two parts, which may be connected either in parallel for two-wire operation or in series for three-wire operation. The two-wire connection as shown is, as a rule, used only for very small loads on account of the low voltage. Another two-wire

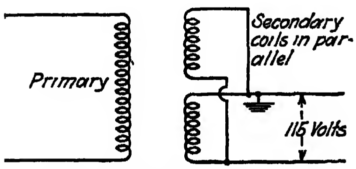

FIG 79.—Transformer connections—single-phase, two-wire.

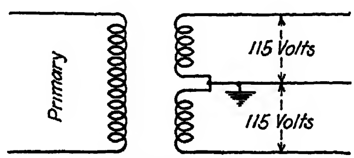

FIG. 80.—Transformer connections—single phase, three-wire

connection which is sometimes used, especially for single-phase power loads, is similar to that shown in (2), below, with the middle wire omitted, giving 230 volts between wires

2. *Single-phase, Three-wire, Fig.* 80.—This is the most commonly used connection for general single-phase distribution. Load is balanced between the two 115-volt circuits. With perfect balance, no current exists in the middle wire, the load being in effect carried at 230 volts on the circuit formed by the two outside wires.

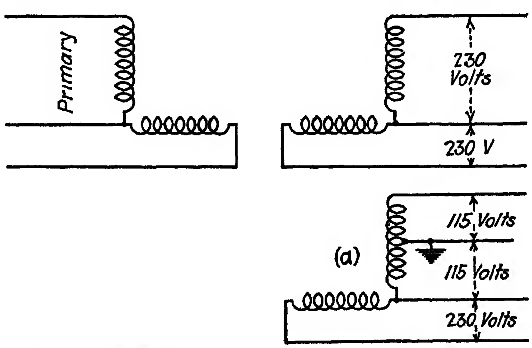

FIG. 81.—Transformer connections—two-phase, three-wire.

3. *Two-phase, Three-wire, Fig.* 81.—Commonly used for serving two-phase motors. Single-phase load can also be served from one transformer by bringing out the midpoint to a fourth wire as in (*a*). Load and voltage are unbalanced thereby, since all the single-phase load is on one phase.

4. *Two-phase, Five-wire, Fig.* 82.—Commonly used for combined single-phase and two-phase power loads. Single-phase load is balanced among the four 115-volt circuits (to neutral). Two-phase motors are connected to the two phases at 230 volts (or 115 volts if desired). This is the most efficient two-phase circuit but requires

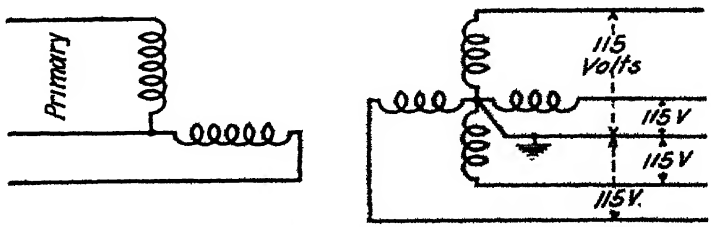

FIG. 82.—Transformer connections—two-phase, five-wire.

a considerable amount of load to obtain a proper balance on so many circuits.

5. *Three-phase, Delta-delta, Fig.* 83.—This connection is commonly used for serving power loads from three-wire primaries, using single-phase transformers (one on each phase). Certain lines of three-phase transformers are also made with this connection.

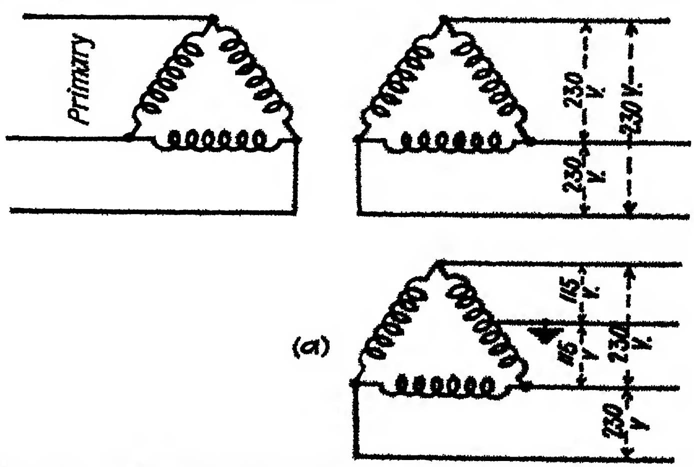

FIG. 83.—Transformer connections—three-phase, delta-delta.

It has the advantage of allowing the transformer across one phase to be disconnected in an emergency and still maintain operations on the other two in open delta, see (8). Single-phase load may also be carried by bringing out the midpoint of one phase to a fourth wire as indicated in (*a*). Load and voltage are thereby unbalanced

since all the single-phase load is on one phase. This connection is discussed in Chap. VII under "Combined Secondaries" and also under "Closed Delta versus Open Delta for Combined Load."

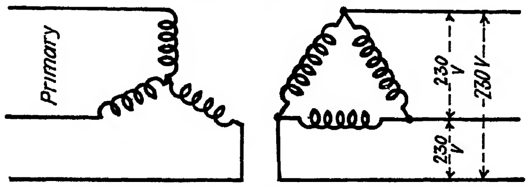

FIG. 84.—Transformer connections—three-phase, Y(star)-delta.

6. *Three-phase, Y-delta, Fig.* 84.—This connection is probably the most common for three-phase transformers. It is also used with four-wire primaries (4,000 volt, etc.) since standard ratio transformers (2,300/230 volt) give proper secondary voltage when

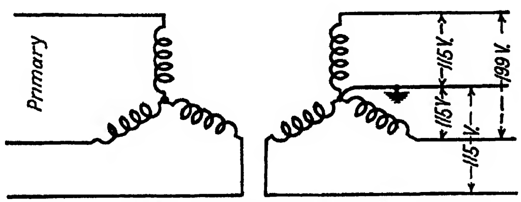

FIG. 85.—Transformer connections—three-phase, Y-Y.

thus connected. A similar connection to (*a*) in Fig 83 may also be used on the secondary.

7. *Three-phase, Y-Y, Fig.* 85.—This connection is chiefly used for serving Y-connected, combined single-phase and three-phase

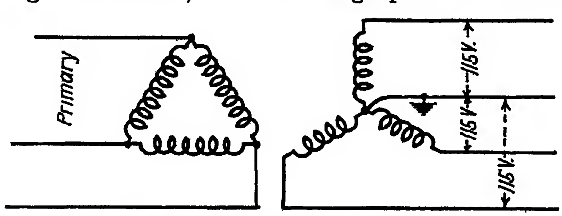

FIG. 86.—Transformer connections—three-phase, delta-Y.

secondary systems from four-wire (4,000-volt) primary mains, using single-phase transformers. Single-phase load is balanced on the three 115 volt (to neutral) circuits and three-phase loads connected at 199 volts on the three phases. The Y-connected

secondary is further discussed in Chap. VII under "Combined Secondaries."

8. *Three-phase Delta-Y, Fig.* 86.—This connection is used to serve Y-connected secondary systems from three-wire primary.

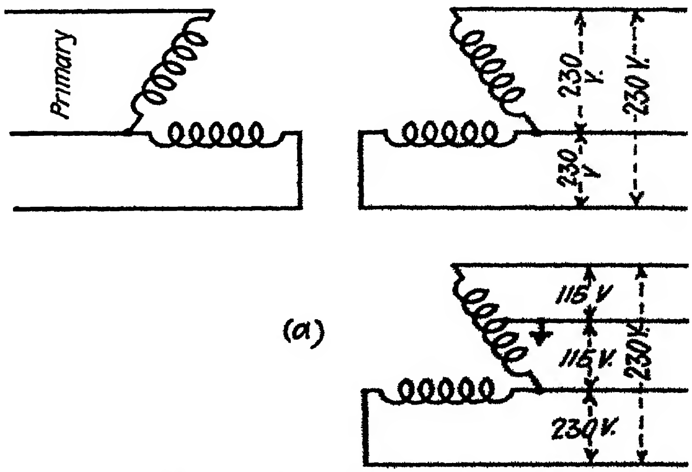

Fig. 87.—Transformer connections—three-phase, open-delta.

It is not commonly used otherwise for distribution transformer connections.

9. *Three-phase, Open-delta, Fig.* 87.—Three-phase loads can be carried with two single-phase transformers by this connection. It is quite commonly used as a temporary emergency connection

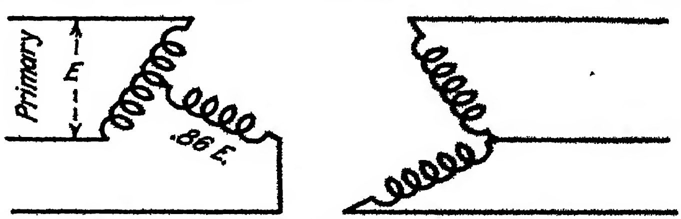

Fig. 88.—Transformer connections—three- to two-phase (*Scott*).

although the voltages are unbalanced considerably. It can be used for single-phase load also as indicated in (*a*) and it is shown below that for combined loads of a certain character this is a very advantageous connection. On the open-delta connection, with two transformers of the same size, only 86 per cent of the total capacity of the transformers (in balanced three-phase load) can be carried since line or Y current passes through both transformers.

10 *Three-phase to Two-phase (Scott), Fig.* 88.—Two-phase loads are quite often served from three-phase primary systems The connection shown can be quite simply made with standard transformers if one transformer has an 86 per cent tap. The two-phase secondary may also be connected as four-wire or five-wire as shown in Figs. 81 and 82, if desired.

Autotransformer.—While not as commonly used on distribution circuits as the two-circuit transformer already discussed, the autotransformer should be well understood since it has certain uses, notably for boosters and for balance coils.

Essentially, the autotransformer consists of a single coil wound on an iron core with three terminals brought out, one at each end of the coil and one from an intermediate tap whose location depends on the voltage ratio desired, see Fig 89. The high voltage circuit is connected to the end terminals *a* and *c*, the low voltage circuit to one end terminal and the intermediate terminal *a* and *b*. The action of the transformer is similar to that of a two-circuit transformer in that the core is magnetized by a magnetizing current from the primary circuit and the interlinkage of this magnetic flux with the coil produces a counter-electromotive force in the coil. If, for example, the primary voltage is applied across *a-c*, an electromotive force very nearly equal to it is produced in the coil from *c* to *a* opposing the passage of any considerable amount of current. If, however, an exterior secondary circuit is connected from *a* to *b*, the voltage across that circuit bears the same ratio to the total voltage *a-c* as the number of turns in the coil from *a* to *b* bears to the total number of turns from *a* to *c*. Current will flow in the secondary circuit in inverse proportion to its impedance. This current divides at *b* as shown by the arrows, part flowing from *b* to *a* through the coil, the remainder from *b* to *c* and thence through the exterior primary circuit to *a*, forming the primary current. The proportion in which the current divides at *b* is such as to balance the magnetization caused thereby in the two parts of the coil, *i.e.*, inversely as the number of turns in the two parts. For example, assume 15 turns in the whole coil from *a* to *b*, 10 of which are in

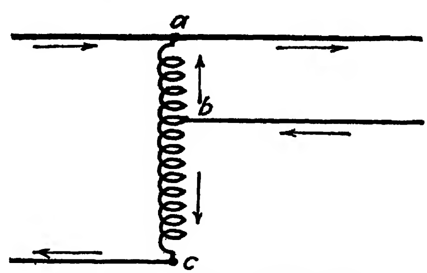

FIG 89 —Autotransformer.

a-b and 5 in *b-c*. The secondary voltage *a-b* is $10/15 = 2/3$ the primary voltage *a-c*. The current in *b-a* is $5/10 = 1/2$ that in *b-c*. Hence, the primary current (same as current in *b-c*) is equal to one-third the secondary current which is equal to the sum of the currents in *b-c* and *b-a*. This is as might be expected from the relation between primary and secondary voltages.

Autotransformers are sometimes used for supplying primary circuits of one voltage from primary circuits of another voltage, especially as more or less temporary installations during operations of changing the primary voltage of a system, as from 2,300 to 4,600 volts. If an ungrounded system is used, it should be remembered that an accidental ground on one side of the higher voltage circuit, as indicated in Fig. 90, will impose the full volt-

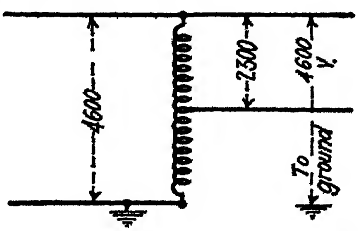

FIG. 90.—Two-to-one autotransformer with ground on high side.

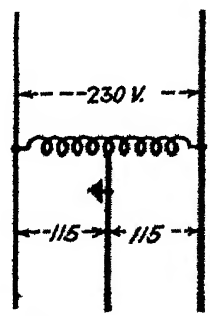

FIG. 91.—Distribution transformer connected as an autotransformer.

age of that circuit on the lower voltage circuit (line to ground), which may be dangerously high for some of the apparatus or cables connected to it.

Autotransformers as boosters (or bucks) are quite commonly used on primary circuits to increase (or decrease) the voltage somewhat at certain points. For this purpose the ordinary distribution transformer is quite often used, connected as an autotransformer as shown in Fig. 91. More details on this connection are given in Chap. X.

Small autotransformers, called "balance coils," are often used on secondary circuits either to obtain a 115-volt, three-wire circuit from a 230-volt, two-wire circuit (used in industrial plants where the main service is 230 volts, three-phase and a small amount of lighting is to be carried) see Fig. 92, or to balance a load which is connected at 115 volts (or largely unbalanced on a three-wire,

10 *Three-phase to Two-phase (Scott), Fig.* 88.—Two-phase loads are quite often served from three-phase primary systems The connection shown can be quite simply made with standard transformers if one transformer has an 86 per cent tap. The two-phase secondary may also be connected as four-wire or five-wire as shown in Figs. 81 and 82, if desired.

Autotransformer.—While not as commonly used on distribution circuits as the two-circuit transformer already discussed, the autotransformer should be well understood since it has certain uses, notably for boosters and for balance coils.

Essentially, the autotransformer consists of a single coil wound on an iron core with three terminals brought out, one at each end of the coil and one from an intermediate tap whose location depends on the voltage ratio desired, see Fig 89. The high voltage circuit is connected to the end terminals *a* and *c*, the low voltage circuit to one end terminal and the intermediate terminal *a* and *b*. The action of the transformer is similar to that of a two-circuit transformer in that the core is magnetized by a magnetizing current from the primary circuit and the interlinkage of this magnetic flux with the coil produces a counter-electromotive force in the coil. If, for example, the primary voltage is applied across *a-c*, an electromotive force very nearly equal to it is produced in the coil from *c* to *a* opposing the passage of any considerable amount of current. If, however, an exterior secondary circuit is connected from *a* to *b*, the voltage across that circuit bears the same ratio to the total voltage *a-c* as the number of turns in the coil from *a* to *b* bears to the total number of turns from *a* to *c*. Current will flow in the secondary circuit in inverse proportion to its impedance. This current divides at *b* as shown by the arrows, part flowing from *b* to *a* through the coil, the remainder from *b* to *c* and thence through the exterior primary circuit to *a*, forming the primary current. The proportion in which the current divides at *b* is such as to balance the magnetization caused thereby in the two parts of the coil, *i.e.*, inversely as the number of turns in the two parts. For example, assume 15 turns in the whole coil from *a* to *b*, 10 of which are in

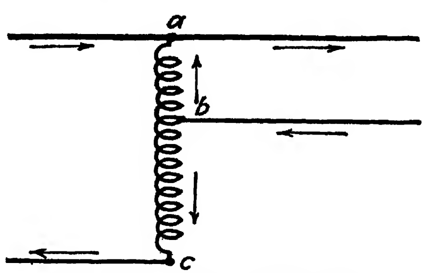

FIG 89 —Autotransformer.

a to *c* is equal to the *sum* of the normal voltages *a-b* and *c-d*, the transformer is said to have *additive polarity*. If the voltage so measured is equal to the *difference* of voltage *a-b* and *c-d*, the transformer is said to have *subtractive* polarity. Most distribution transformers are now built with additive polarity. If it were found necessary to tie together two transformers, one with additive and one with subtractive polarity, it would be necessary to reverse the connection of one, that is, connect *c* terminal on one transformer with *d* terminal on the other.

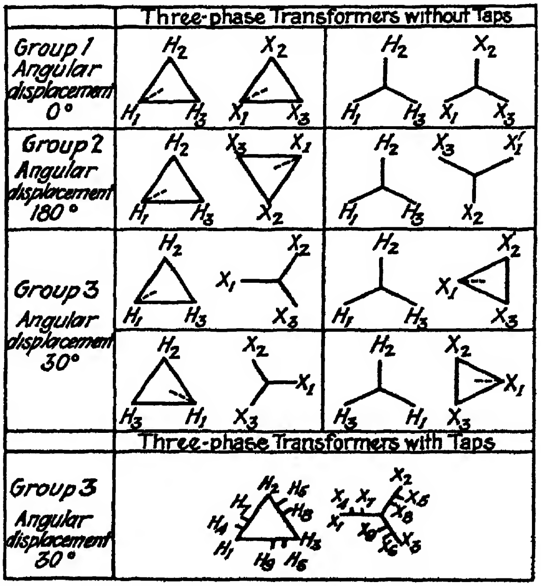

FIG. 94.—Standard transformer vector diagrams and lead markings

Three-phase Transformers.—The polarity of three-phase transformers is not so simple, considerations of phase rotation, marking of leads, and type of internal connection being involved. Figure 94 gives voltage diagrams of the various types of standard connections. Figure 95 shows the relation of voltages when one primary lead and one secondary lead are tied together, with delta-delta and Y-Y transformers. It is apparent that when three-phase transformers are paralleled, care must be taken that they are of the same polarity.

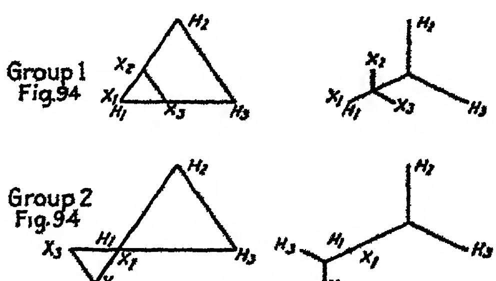

FIG. 95.—Voltage relations of three-phase transformers (delta-delta and Y-Y) with one primary and one secondary lead tied together

Single-phase versus Three-phase Transformers.—For carrying three-phase loads, three-phase transformers are available or banks of single-phase transformers may be used. The question

10 *Three-phase to Two-phase* (*Scott*), *Fig.* 88.—Two-phase loads are quite often served from three-phase primary systems The connection shown can be quite simply made with standard transformers if one transformer has an 86 per cent tap. The two-phase secondary may also be connected as four-wire or five-wire as shown in Figs. 81 and 82, if desired.

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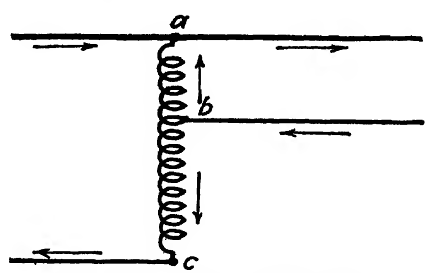

FIG 89 —Autotransformer.

formers, although being all carried on one phase of the primary. Figure 96 indicates such a connection. If all three transformers are of the same size and of similar characteristics, the impedance of the path which secondary current may take through *a-c-b* is twice that through *a-b*. These two paths being in parallel, one-third of the current will pass through *a-c-b* and two-thirds through *a-b*. The capacity of the bank for carrying single-phase current is hence 50 per cent greater than for single-phase transformer *a-b* alone. For example, a bank of three 50-kv-a. transformers could carry 75 kv-a. single-phase load on any one phase. This is a wasteful method of using transformers capacity, however, if single-phase load only is to be carried.

Closed Delta and Open Delta for Combined Load.—It very often occurs that both three-phase and single-phase service is required by a customer or group of customers and it is convenient to carry both on the same transformer installation. Such a combined installation should be used only where the starting current of the largest motor connected is small enough in proportion to the lighting load that transformers used can carry it without producing undesirable dips in the voltage at the lamps. Various connections for accomplishing this are discussed in Chap. VII under "Secondary Networks." If the delta connection is to be used, there are two choices, the closed delta, using three transformers with the one on the lighting phase larger than the other two, and open delta, using one large transformer on the lighting phase and one smaller one on one of the other phases.

Where the three-phase load predominates and the single-phase is much smaller, the closed-delta installation, with one transformer somewhat larger than the others perhaps, is usually the better of the two types. When the single-phase load predominates, however, *i.e.*, is at least as large in kilovolt-amperes as the three-phase, it will be found that the open-delta connection is preferable. It can be shown that a better utilization of transformer capacity is obtained and less voltage unbalance at full combined load. The reason for this is indicated in Figs. 97 and 98 in which an analysis of the voltage and current vectors of the two connections is shown. On Fig. 97 for the closed delta it is assumed that the transformers are of similar characteristics with one (*X-Z*) three times as large as the other two in order to carry the lighting load. The load is divided into component currents across each phase. It is apparent that the large trans-

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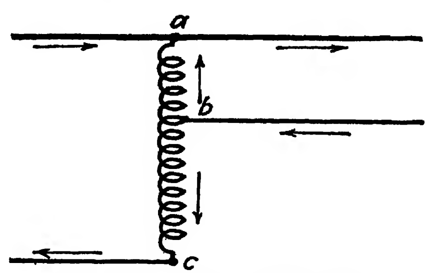

FIG 89 —Autotransformer.

In Fig. 98 the resulting open-delta currents are shown when one phase is opened and its current added (in reverse phase) to those already in the other two phases.

Figure 98 (*a*) indicates that if one phase (*Y-Z*) is opened, the currents in the other two phases are not increased greatly and the power factor in *X-Y* is considerably improved, that in *Z-X* being lowered slightly. The result, for all practical purposes, is that the two transformers are operating at very nearly unity power factor and at not much greater current than they carried when the third transformer was present. Thus the advantages claimed above. Figure 98 (*b*) shows the importance of selecting the proper phase to

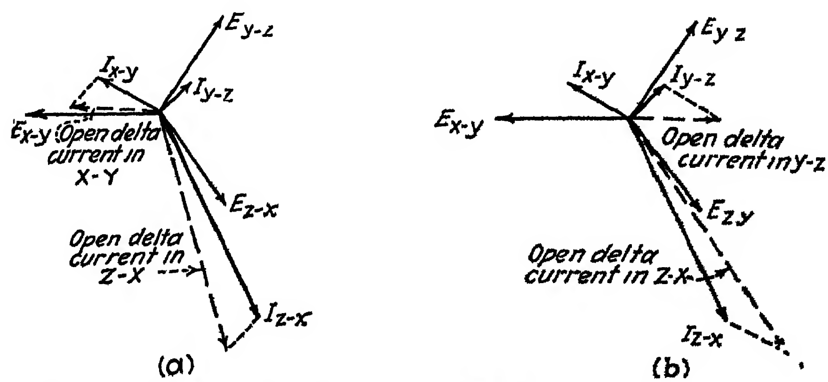

FIG. 98.—Comparison of open- and closed-delta currents: (*a*) phase *Y-Z* open; (*b*) phase *X-Y* open.

open. If the wrong phase is opened (*XY*), the reverse of the above described conditions is experienced. Care should be taken that the power transformer of the open delta be connected from the phase wire common to the two transformers to the phase which *lags* it by 120 deg., the lighting transformer being connected from the common phase to the phase which *leads* it by 120 deg.

A further advantage of the open delta is that if the large lighting transformer drops out for any reason, its load is not thrown on the small power transformers as it is with the closed delta. If used in bank or network with other transformer banks, the open delta makes a much simpler system to design and operate than the closed delta.

It would seem from the above that advantages shown for the open-delta connection warrant its recognition as not only a temporary expedient or more or less of a makeshift but also as an

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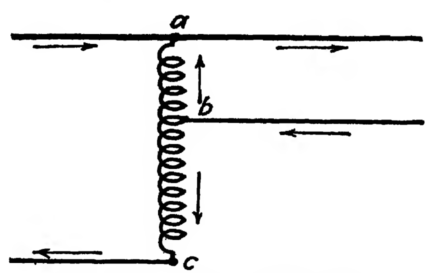

FIG 89—Autotransformer.

Voltage Drop—Closed Delta or Open Delta.

$$V_n = [I(c_n \cos \phi + d_n \sin \phi) + I_0(e_n \cos \phi_0 + f_n \sin \phi_0)]\frac{100}{E} \text{ in per cent} \quad (20)$$

(subscript n refers to the particular transformer 1, 2, or 3 under consideration)

Closed Delta

Where

$$c_1 = r_1(A + 1) - x_1B$$
$$c_2 = r_2(1 - 0.5A - 0.866B) + x_2(0.5B - 0.866A)$$
$$c_3 = r_3(1 - 0.5A + 0.866B) + x_3(0.5B + 0.866A)$$
$$d_1 = x_1(A + 1) + r_1B$$
$$d_2 = x_1(1 - 0.5A - 0.866B) - r_2(0.5B - 0.866A)$$
$$d_3 = x_3(1 - 0.5A + 0.866B) - r_3(0.5B + 0.866A)$$
$$e_1 = r_1(1 - a_1) - x_1b_1$$
$$e_2 = 0.5(r_2a_1 + x_2b_1) + 0.866(x_2a_1 - r_2b_1)$$
$$e_3 = 0.5(r_3a_1 + x_3b_1) - 0.866(x_3a_1 - r_3b_1)$$
$$f_1 = x_1(1 - a_1) + r_1b_1$$
$$f_2 = 0.5(x_2a_1 - r_2b_1) - 0.866(r_2a_1 + x_2b_1)$$
$$f_3 = 0.5(x_3a_1 - r_3b_1) + 0.866(r_3a_1 + x_3b_1)$$

Open Delta

$$c_1 = 1.5r_1 + 0.866x_1$$
$$c_2 = 1.5r_2 - 0.866x_2$$
$$c_3 = 1.5(r_1 + r_2) - 0.866(x_1 + x_2)$$
$$d_1 = 1.5x_1 - 0.866r_1$$
$$d_2 = 1.5x_2 + 0.866r_2$$
$$d_3 = 1.5(x_1 + x_2) + 0.866(r_1 + r_2)$$
$$e_1 = r_1$$
$$e_2 = 0$$
$$e_3 = 0.5r_1 - 0.866x_1$$
$$f_1 = x_1$$
$$f_2 = 0$$
$$f_3 = 0.5x_1 + 0.866r_1$$

Size.—Distribution transformers are pretty well standardized as to kilovolt-ampere capacity by the manufacturers as follows:

Single-phase Transformers.—1½, 3, 5, 7½, 10, 15, 25, 37½, 50, 75, 100, 150, 200 kv-a.

Three-phase Transformers.—5, 7½, 10, 15, 25, 50, 75, 100, 150, 200 kv-a.

It is probably not good policy, in most cases, for an operating company to carry all of these standard sizes in their own stock. In the smaller sizes especially, some of the intermediate sizes, such as 3 and 7½, can be omitted without inconvenience. The larger sizes, over 100 kv-a., are more in the power-transformer class and

10 *Three-phase to Two-phase (Scott), Fig.* 88.—Two-phase loads are quite often served from three-phase primary systems The connection shown can be quite simply made with standard transformers if one transformer has an 86 per cent tap. The two-phase secondary may also be connected as four-wire or five-wire as shown in Figs. 81 and 82, if desired.

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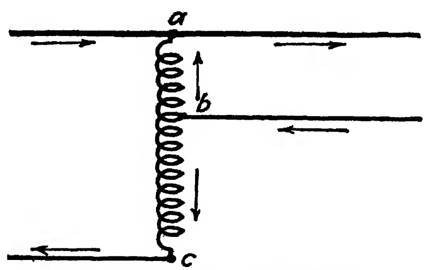

FIG 89—Autotransformer.

short duration, such as the characteristic lighting load, will not continue long enough to bring about such a temperature. Conversely, a much higher load of this characteristic may be applied before the maximum allowable temperature is reached. That is, with characteristic lighting load, a distribution transformer may be expected to carry a load of considerably more than its rating without injury. Figure 99 illustrates this fact, showing the results of a test on a 5-kilovolt-ampere single-phase distribution transformer with a load of 175 per cent of its rating, *i.e.*, 8.75-kilovolt-ampere peak.[1] Hot spot temperatures were taken with thermocouples introduced into the windings at various points.

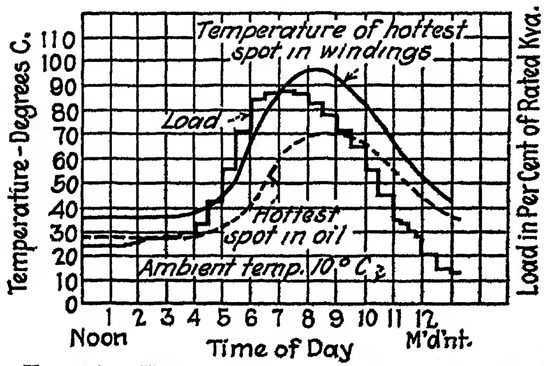

FIG. 99.—Test on 5 kv-a distribution transformer with 175 per cent characteristic lighting load.

Another factor which favors the increase in allowable loading, in some localities at least, is the fact that maximum load for the year is not likely to occur with an ambient temperature of 40°C. (104°F.). Peak load for lighting usually comes at night and the maximum peak for the year comes in the winter. In northern latitudes at least, this is accompanied by an ambient temperature much below 104°F., more likely to be 32°F. or below. This, of course, with outdoor transformers, reduces the hot-spot temperature for a given load accordingly and hence allows still greater increase of loading beyond normal rating. Of course, this condition is not true for all transformers carrying lighting load. If a considerable amount of range load is present, for example, enough to create the peak, the maximum load may come at 6 o'clock or earlier and be as great (or greater) in summer as in winter. Such loads have a short peak, similar to that for characteristic lighting load, however, so the first factor discussed remains more or less the same. A quite complete exposition of the possibilities of loading transformers is given in a *Serial Report*, Overhead Systems Committee, National

[1] COLE, HAROLD, "The Loading of Distribution Transformers." Paper presented before Annual Meeting of Great Lakes Division, N.E.L.A., Sept. 25, 1924.

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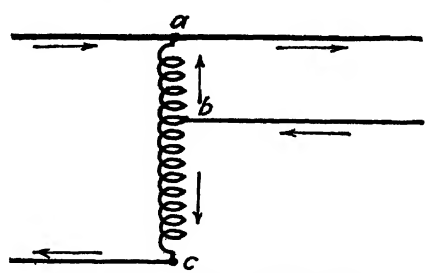

FIG 89 —Autotransformer.

use of the maximum allowable temperature as a limit for transformer loading which should be carefully considered before it is employed to any great extent. These are as follows:

1. While the 105°C. temperature limit is assumed to be a safe operating temperature limit, it is claimed by some that even at this temperature, the life of the insulation is decreased from what it would be if operated only at lower temperatures.

2. Even if a transformer could be loaded with safety to 150 or 200 per cent of its rating, the voltage regulation is correspondingly increased. If the allowable regulation at the customer is limited by law or good practice to a certain value, this must be divided between secondary, transformer, and primary line without allowing an undue proportion to any one. With even 150 per cent load, it will be seen from Fig. 101 that the transformer regulation rises to 4 or 5 per cent at ordinary power factors of 90 to 95 per cent. This is often too large a proportion of the total to assign to the transformer. In order to keep within the prescribed limits, the regulation on either primary or secondary or both must be correspondingly decreased. It may or may not be economical to do this. It is a matter for a thorough study of the factors of cost involved.

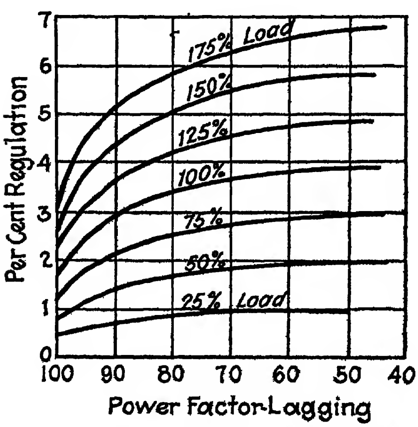

Fig 101.—Regularion of typical 50 kv-a. distribution transformer.

3. The overload capacity allowed by temperature limit may be a very useful quantity as a reserve capacity to take care of sudden unforeseen increases in load. As a rule, line transformers cannot be inspected at very frequent intervals and it is almost impossible to take care of all such increases in load in advance. If the practice is to load transformers to their limit ordinarily, the increase may very well be enough to burn them out.

This factor is of special importance where the system of banking transformers is employed. Here it is anticipated that one transformer in the bank may drop out and its load still be carried on adjacent transformers in the bank. It is essential, therefore, that these adjacent transformers have some reserve capacity to

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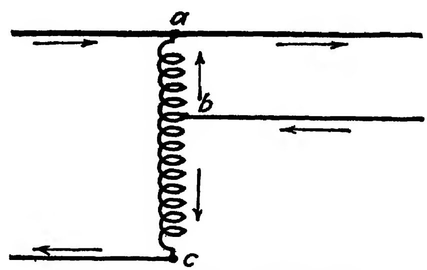

FIG 89—Autotransformer.

In general, it may be said that the most economical condition is that for which the transformer is as near as possible to the load center of the load which it is to carry, is just large enough for the load (taking account of such overload capacity as is deemed advisable under the circumstances), and with secondary just large enough to give the limiting voltage regulation to the farthest customer. Where one large concentrated load predominates, the best location for the transformer is, naturally, near that load. With a limited number of standard sizes of transformers and secondary wire and with continually increasing loads, it is impossible, of course, to maintain such conditions generally over the system, but it is the ideal toward which average conditions should be pointed.

Banking Transformers.—The practice of tying transformers together on the secondary side into secondary banks has been

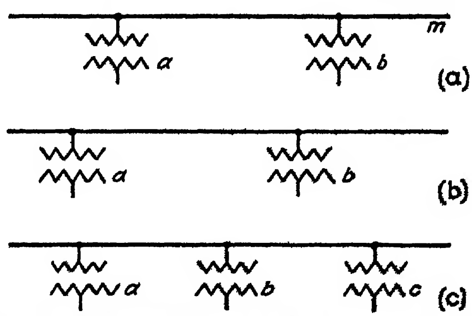

FIG. 102.—Transformers in secondary banks.

taken up before (Chap. VII), as to its advantages and disadvantages and also somewhat as to the performance of transformers. A little more will be given here on the distribution of load under normal and emergency conditions among transformers in such banks. The figures given refer especially to overhead systems, where the secondary impedance is relatively high, although the same methods can be followed for underground systems.

Referring to Fig. 102(*a*), if *a* and *b* are two transformers of the same size and characteristics, symmetrically placed on the secondary, and the load is uniformly distributed, both transformers will be loaded equally. If one drops out, the other will take up its load as far as possible, limited only by the change in load due to voltage drop. For lighting load, the current varies approximately as the 0.58 power of the voltage (very nearly as

10 *Three-phase to Two-phase (Scott), Fig.* 88.—Two-phase loads are quite often served from three-phase primary systems The connection shown can be quite simply made with standard transformers if one transformer has an 86 per cent tap. The two-phase secondary may also be connected as four-wire or five-wire as shown in Figs. 81 and 82, if desired.

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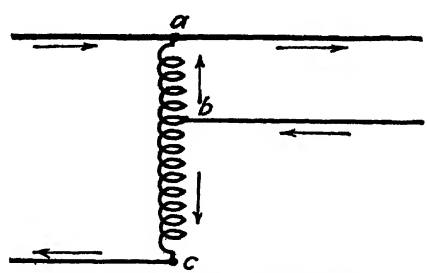

FIG 89—Autotransformer.

voltage drop in the transformers, including consideration of line drop. For example, with all three the same size, and 3 per cent maximum normal drop, assume *c* drops out. If *b* took all of *c*'s load, without dropping any of its own, conditions would be as in the first case described. The voltage at *b*, however, would be 2 per cent lower than formerly. Hence, it would pass along some of the load between *a* and *b* to *a*, relieving its load somewhat and raising its voltage. A balance is thus reached when sufficient load is transferred to equalize the voltage at some point between the two. In this case, this occurs when somewhere in the neighborhood of 7 or 8 per cent the original load of *b* is transferred to *a*. In other words, most of the load of *c* is thrown on the adjacent transformer *b*. If the transformers are not of the same size but *b* is larger compared with *c*, the result may be safe operation. If *b* is smaller than *c*, however, somewhat more of its load will be transferred to *a* but even so the overload may be disastrous.

Such analyses might be continued indefinitely, but enough has been given to indicate the method which may be followed. For more than three transformers, or for arrangements other than a straight bus secondary, the analysis will be much more difficult.

In general, it may be said that in banking transformers, the following rules should be observed.

1. Each transformer should be tied in to at least two adjacent transformers where possible, *i.e.*, a ring or network system.

2. Where this is not possible and a transformer must be placed on the end of a line with only one adjacent transformer, that adjacent transformer should have sufficient reserve capacity to carry most of the end transformer's load (80 per cent at least).

3. For any part of the bank, each transformer should have adjacent to it transformers with sufficient reserve capacity to carry at least 80 per cent of its load.

4. It is preferable not to have very large and very small transformers in the same bank, but this is not prohibitive if they are of proper capacity for the load and for reserve capacity, and properly arranged.

5. Transformer fuses must be of proper size to allow the reserve capacity to be effective.

Testing and Inspection.—Practice among different companies in the matter of testing and inspecting line transformers differs widely, ranging from no periodic tests or inspection at all (depending on service interruptions or low voltage to indicate damaged

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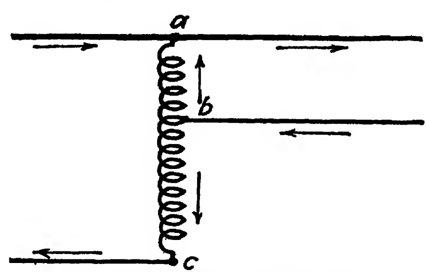

FIG 89 —Autotransformer.

ing load, or load where the peak is likely to be at some other time of day, recording meter checks are taken over a period of a day or so. In the spring, after the winter peak is well past and the weather is warmer, a careful inspection is made, including a visual inspection of transformer oil. In the case in question, the practice is to bank several distribution transformers together on the secondary side, hence a transformer may be out of service for some time, especially during the summer period of light loading, without giving rise to service complaints. Hence, another inspection, especially to discover blown fuses and any burned-out transformers, is made after the summer lightning season is past and before the winter load begins to come on. Naturally, where transformers are not banked, such damage will be immediately evidenced by an interruption to service and the inspection will not be necessary. Three-phase transformers are tested and inspected once a year, usually during the summer. Occasional special tests in particular cases both on single-phase and three-phase transformers are also necessary, of course, where a large increase or decrease in load is known or expected. With such a system of test and inspection, it is possible to keep the transformers loaded to a fairly high average percentage of their capacity without fear of unforseen load increase causing dangerous overloads. Also the periodic voltage check is a valuable index of service condition.

The question of using temperature indicators as a basis for loading transformers instead of spot-load readings with an indicating ammeter has been discussed to some extent above. The disadvantages of the ammeter method are the facts that the tests indicate only the load at the particular time of day and the particular day in the year when they are taken and no indication is had of what it is at any other time, or whether that reading is anywhere near the actual yearly peak. Also, the test requires a considerable amount of time for each transformer and skilled testers to make it. The temperature indicator avoids these faults to some extent, being installed on the transformer and ready to show maximum load, and in some types also an indicating reading of load at the time, and requiring only a quick visual inspection to determine if it has been tripped by overload. On the other hand, the temperature indicators so far produced cannot be depended upon to indicate with any degree of accuracy actual load in kilovolt-amperes or its balance or direction, and these are important

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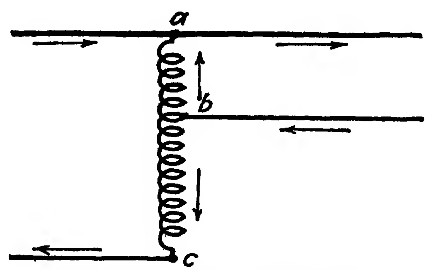

FIG 89 —Autotransformer.

CHAPTER X

VOLTAGE DROP AND REGULATION

Since all apparatus for the utilization of electric current is designed for some particular applied voltage and is limited to a certain range of voltage, above and below that rating, for satisfactory operation, it might be said that the task of the distribution engineer is essentially that of supplying every customer with a voltage which does not fall below a certain defined value under the heaviest load condition nor rise above a certain other defined value at the time of lightest load. The whole distribution system, including transmission, substation apparatus, feeders, transformers, and secondaries, is designed on the basis of transporting the maximum amount of current which the customer will require, from the generator to his service switch, and delivering it at a voltage, not only of a satisfactory value under this maximum load, but also of a satisfactory value at any other load from 0 to that maximum, *i.e.*, with a satisfactory range of regulation. Regulation is defined as the percentage which the difference between full-load voltage and no-load voltage bears to full-load voltage. Just what the normal service voltage should be and what should be considered a satisfactory range will depend on local conditions somewhat, type of service, etc., and is sometimes governed by law. In previous chapters these points have been discussed to some extent for various types of load. In general it may be said that, since general service motors are usually given a guarantee of satisfactory operation at 10 per cent above or below rated voltage, and rated voltage is ordinarily 220 volts, these limits (198 to 242 volts) should not be exceeded. For lighting load, a total range of 8 to 10 per cent in regulation is usually about as large as should be considered for good service, the actual limits depending on the rating of lamps used, whether motors are connected to the same circuits, etc. For a system serving miscellaneous light and power and using 115-volt lamps, for example, a satisfactory range for general service might be chosen as 110 volts minimum to 120 volts maximum, the maxi-

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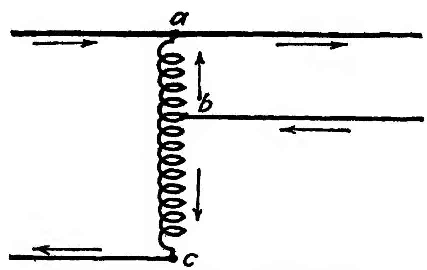


FIG 89 —Autotransformer.

Secondary line drop = 4 volts at full load.

$$240 \times 10 = 2{,}400 \text{ volts}$$
$$2{,}400 - 40 = 2{,}360 \text{ volts on line.}$$

2,360 volts − 80 volts line drop − 40 volts transformer drop = 2,240.

$\frac{2{,}240}{10} = 224$ volts; 224 − 4 volts secondary drop = 220 volts at customer

Voltage at customer at no load same as at generator, since line and transformer drops are 0 at 0 load.

$$\text{Regulation} = \frac{240 - 220}{220} = 9.1 \text{ per cent.}$$

3. Assume the same conditions as in 2 except that the step-up transformer has taps inserted to give 50 volts higher than a straight 10 to 1 ratio and the step-down transformer also has taps to give 5 volts higher (on the secondary) than a straight 10 to 1 ratio.

Then,

$$240 \times 10 + 50 = 2{,}450 \text{ volts; } 2{,}450 - 40 = 2{,}410 \text{ volts on line.}$$

2,410 − 80 (line drop) − 40 (step-down transformer drop) = 2,290.

$\frac{2{,}290}{10} + 5 = 234$ volts on secondary; 234 − 4 (secondary drop) = 230 volts at customer at full load.

This is 10 volts less than at the generator. However, with the transformer taps cut in, the no-load voltage is raised as well as the full-load voltage, hence the no-load voltage at the customer is

$$240 \times 10 + 50 = 2{,}450.$$
$$\frac{2{,}450}{10} + 5 = 250 \text{ volts at no load.}$$
$$\text{Regulation} = \frac{250 - 230}{230} = 8.7 \text{ per cent.}$$

The above examples illustrate the fact that although the customer's voltage at full load may be increased by the use of higher generator voltage or odd ratio transformers (taps) the regulation or range in voltage from no load to full load is not thereby improved. This can only be done by employing some means for changing the voltage as the load changes, raising it at high loads and lowering it at lower loads. The most commonly used means for accomplishing this are:

1. By varying the generator voltage.
2. By tap changing (under load) transformers or their equivalent.
3. By synchronous condensers operated as regulators.
4. By induction regulators.

The first three of these methods belong to the transmission system so will not be taken up in detail here. They may serve,

however, to take care of a greater part of the regulation of the system up to the substation from which distribution feeders are run. The substation pressure may even be varied somewhat during the day by these means, to take care of characteristic periodic changes in load. For example, the substation bus might be kept at an equivalent pressure of 120 volts during the day when the heavy load is on and dropped to 118 volts at night when the load is off, by varying the generator voltage.

Induction Regulator.—The most common means now employed to correct fluctuations in voltage on distribution feeders is the induction regulator. It also serves to adjust the voltage on the line in such a way that a practically constant voltage is maintained at a point some distance from the substation, if desired, under all variations in the load.

It is not within the province of this work to take up in any detail the theory and design of the induction regulator.[1] It is sufficient to say here that the induction regulator is, in effect, a variable ratio transformer added to a line to raise or lower the voltage as desired.

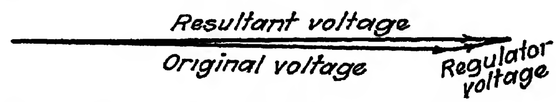


FIG. 104—Vector diagram for single-phase induction regulator.

A *single-phase* regulator adds or substracts a voltage very nearly *in phase* with the line voltage as shown in Fig. 104. This voltage changes in value with the operation of the regulator from neutral to full boost (or buck) but does not change in its phase relation.

A *three-phase* regulator, on the contrary, adds to the voltage across each phase a voltage of a constant value no matter what the position of the regulator may be. That voltage is *not in phase* with the line voltage, however, except at full boost or full buck position, see Fig. 105. At any intermediate position the voltage is out of phase with the line voltage, hence the resultant of the two is less than the arithmetical sum an amount depending on the angle between them. At a little less than 90 deg. the regulator is in neutral and no voltage is added or subtracted. It should be noted that the three-phase induction regulator rotates the phases of the line voltage out of their original position due to the addition of another voltage vector, *i.e.*, the

[1] For this the reader is referred to GEHRKENS, E. F., "The Induction Voltage Regulator," General Electric Company.

resultant voltage at any position (including neutral) is somewhat out of phase with the original voltage. Hence, if two lines, each with a three-phase regulator connected, are tied together, unless the two regulators are in exactly the same position, the resulting line voltages are out of phase and a circulating current is likely to result.

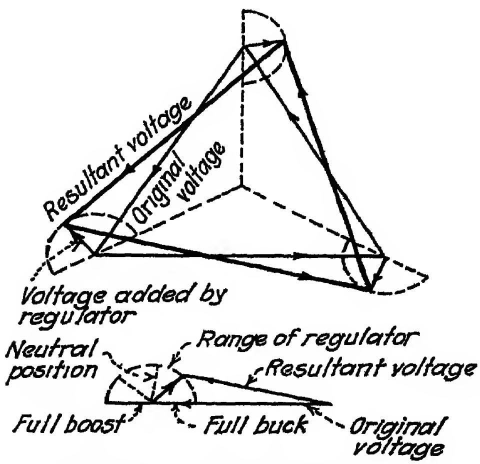


FIG. 105.—Vector diagram for three-phase induction regulator.

In some cases it is advantageous to use *single-phase regulators* instead of a three-phase regulator for *regulating a three-phase line.* Where the load is unbalanced to any considerable extent, balanced voltage at the point for which the voltage is compensated cannot be obtained with a three-phase regulator since the three-phase regulator boosts or bucks all phases in the same amount. Figure 106 indicates several possibilities with the use of single-phase regulators.

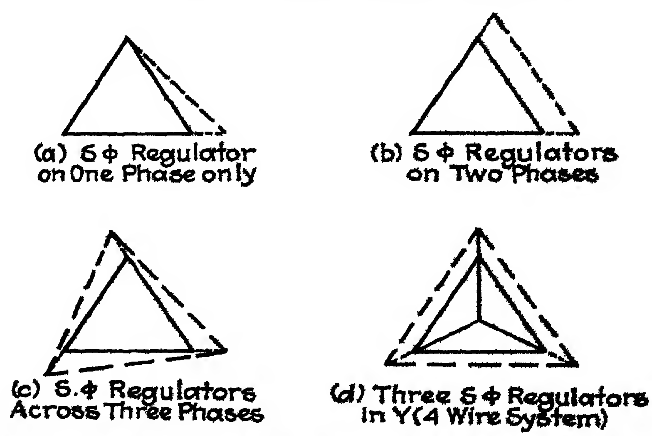


FIG. 106.—Vector diagram for regulation of three-phase lines by single-phase regulators.

Figure 106 (*a*) regulates on one phase only, thereby affecting a second phase to a lesser degree and the third phase not at all. It is not much used.

Figure 106 (*b*) accomplishes fairly good results, two phases being accurately controlled, the change in the third being dependent on the amount of regulation in the other two.

Figure 106 (*c*) results in accurate control for all three phases. A change in one phase is more or less dependent on the changes in the other two and hence the three regulators do not operate entirely independently. It is a stable condition, however.

Figure 106 (*d*) is used for four-wire systems, each phase being controlled independently. The same connection can be used for a three-wire system also. With this connection the voltage of the regulator is Y voltage, *i.e.*, $1/\sqrt{3}$ that required for the connection shown in Fig 106 (*c*).

Size of Regulators.—An induction regulator is rated according to the percentage which it can add or subtract to the applied voltage. For example, a 10 per cent regulator is capable of increasing the voltage to any value up to 10 per cent above the applied voltage or decreasing it to any value down to 90 per cent of the applied voltage, a total range of 20 per cent. For example, suppose it is desired to maintain a constant voltage of 115 volts at some point out on the line, the voltage drop on the line from the substation being 10 volts at full load. The voltage on the line side of the regulator must be raised from 115 volts at no load to 125 volts at full load. Suppose the substation voltage varies, due to drop in the transmission system, from 125 volts at no load to 115 volts at full load. Under no-load conditions, therefore, the regulator must buck the substation voltage down from 125 to 115. At full load it must raise it from 115 to 125. The range in regulation is therefore 20 volts, 10 above and 10 below 115 volts. A 10 per cent regulator is required.

The capacity in kv-a. of the regulator which must be used in any given case is based on full-load amperes times the voltage which the regulator can add. Since a 10 per cent regulator adds at full boost 10 per cent of the line voltage, this 10 per cent times full-load current is equal to 10 per cent of full load in kv-a In other words, the necessary capacity in kv-a. of the regulator is the same percentage of full load kv-a. on the line as its rated per cent voltage regulation. This applies to single-phase regulators on single-phase lines and in Y connection on three-phase lines, also to three-phase regulators. For the connections shown in Figs. 106 (*b*) and (*c*) using single-phase regulators in Δ connection on three-phase lines, the capacity is somewhat

different. In the case of three regulators, Fig. 106 (c), since the voltage across any phase is increased, not only by the regulator across that phase but also by the action of the regulator on the adjacent phase, the per cent regulation rating of the regulator is only 67 per cent of the maximum per cent regulation required for line voltage. (For 10 per cent regulation a 6.7 per cent regulator is required, usually a 7.5 per cent standard rating is used.) For the two regulator connections, Fig. 106 (b), full percentage rating is required. The capacity in kv-a. is also affected by the fact that line (Y) current passes through the regulator which is connected for Δ voltage. Hence the total regulator capacity required in either case, Figs. 106 (b), or (c) is 116 per cent of what would be required with a three-phase regulator, that is for 10 per cent regulation 11.6 per cent of load kv-a. is required.

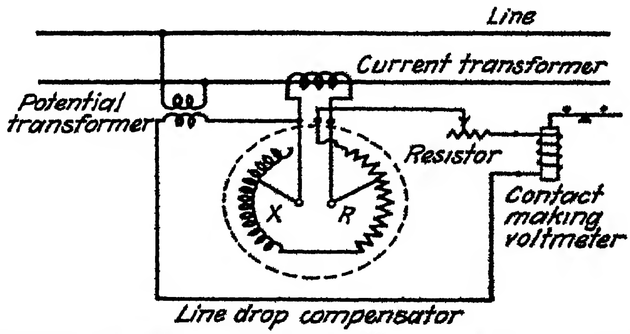


Fig. 107.—Schematic diagram of line drop compensator and contact making voltmeter.

Operation.—The induction regulator may be controlled by hand, the operator causing the voltage to be raised or lowered as desired to meet required conditions as indicated by an indicating voltmeter on the line. They are probably more often operated automatically, however, the control being a contact-making voltmeter which causes the regulator to raise or lower as required to maintain a constant predetermined voltage.

This voltmeter may be connected directly across the line at the regulator terminals in which case a constant voltage is maintained at that point. Where it is desired to regulate the voltage at some distant point such as at the feeding point of a *distribution circuit*, however, a line-drop compensator is used with the contact-making voltmeter connected across it. The line-drop compensator is virtually a small image of the line itself. Reactance and resistance

proportional to those of the line are set on the compensator and a current proportional to the line current is passed over it. The resulting drop is equal (or proportional) to the voltage drop in

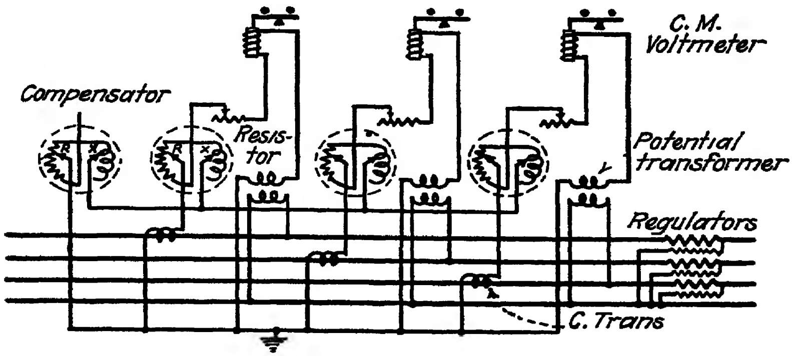


FIG. 108.—Connection of line drop compensators to four-wire circuit.

the line. This is subtracted from line voltage at the regulator terminals thus giving the voltage at the point of compensation, varying with the load. The regulator is then operated so as to maintain the desired voltage at the point for which the compensator is set, the voltage at the regulator terminals being, of course, higher than that whenever load is on. Figure 107 shows a diagram of a line-drop compensator. Figure 108 shows the connection with three single-phase regulators on a four-wire circuit.

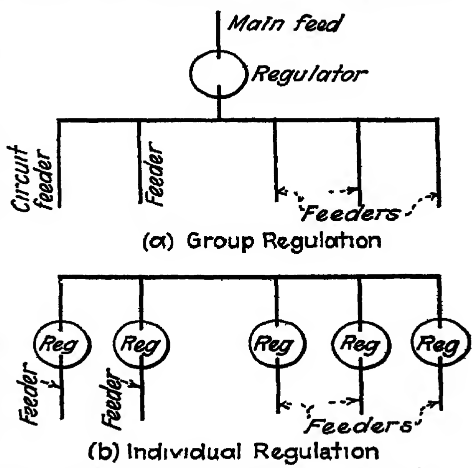


FIG. 109.—Group regulation and individual regulation

Group Regulation.—In practice there are two ways, in general, in which regulators are used. Large regulators are sometimes placed so as to carry a group of lines, *i.e.*, they regulate a bus from which the lines are fed, either to a constant voltage throughout the day or to a voltage which varies somewhat with the total load, Fig. 109 (*a*). This cares for transmission-line fluctuations and, in the latter case, for feeder-line drop somewhat. In case the feeders are of different length, however, the difference in line drop is in no way provided for to give a uniform voltage at the feeder end. Also,

differences in drop due to different loading on the feeders is not compensated. This method is probably most useful where all the feeders in the group are of nearly the same length and comparatively short or where close regulation is not essential, as on lines carrying only power loads. Where the voltage is to be varied according to the load, one feeder may be picked out and the compensator set for its characteristics and its load, or the total load on the regulator may be used.

Individual Feeder Regulation.—Probably the more usual method is to regulate each line individually, Fig. 109(*b*). In this case, if the line has no definite feeding point but branches in several directions and picks up load all the way, some point out on the line should be chosen and the compensator set to give constant

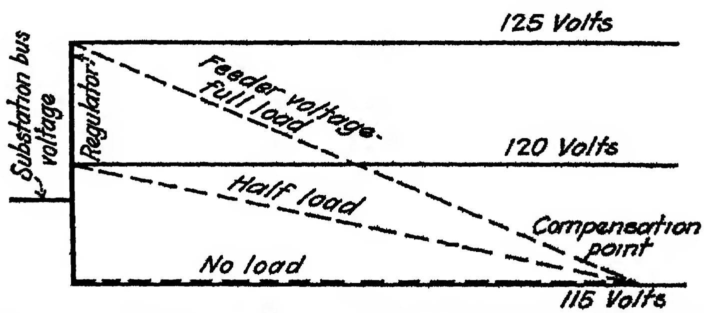


FIG. 110.—Feeder regulation—compensation for a given point.

voltage at that point, Fig. 110. This point should be selected so as to give the best average service voltage conditions, *i.e.*, so that under the heaviest load, the customer farthest out will get voltage not lower than the minimum limit of the voltage range established for the system and at the same time the customer nearest the station will not get voltage higher than the maximum limit of the voltage range, allowing for the possibility that the latter customer may be drawing a light load at this time and hence not getting full voltage drop in his transformer and secondary.

Where the line feeds direct to a definite feeding point before picking up load, see Fig. 38, it is somewhat easier to maintain a more closely limited voltage range. It might seem logical to select the feeding point as the point of compensation and maintain constant voltage there. This is often the practice. It may be seen by studying Fig. 110, however, that, if this is done, full advantage of the regulator action is not taken. The voltage maintained at the

feeding point will be the maximum voltage at any time and the drop from the feeding point to the farthest customer under full load will establish the minimum. If, however, a fictitious point beyond the feeding point is chosen and the compensator set for that point,

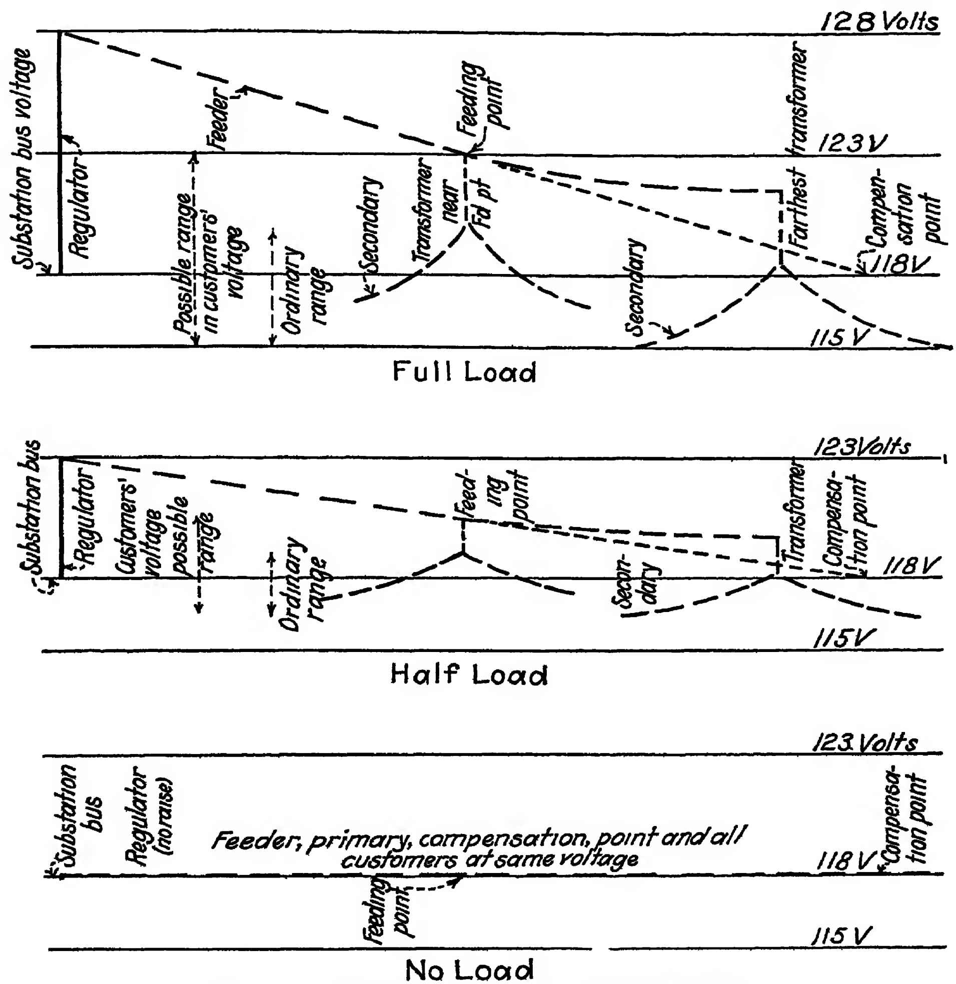


FIG. 111.—Feeder regulation—overcompensation.

allowance for the drop in distribution transformers and secondaries is thus made and better average conditions maintained. Figure 111 shows a typical example. The compensation point is held at 118 volts so that the actual feeding point voltage varies from 118 at no load to 123 at full load. Since the maximum drop to the

farthest customer at full load is assumed to be 8 volts, he will get 115 volts at full load and 118 at no load. The customer near the feeding point will get 118 at no load and not more than 123 at full load—usually not more than 121. Therefore, a probable range of regulation of 115 to 121 is maintained. If the feeding point were maintained at 121, the range would be 113 to 121. This practice is called "overcompensation."

Regulators in Parallel.—On loop-power lines with individual regulators at each end and on feeders individually regulated, serving a multiple feed secondary network, consideration must be given to the questions of stability and possible circulating currents. If single-phase regulators are used on each phase, connected in Y, there is no rotation of phases and hence no circulating current from that cause. If, however, three-phase regulators are used, unless means are taken to keep the regulated voltages in phase with each other or nearly so, there is likely to result a circulating current which may be high enough to be troublesome unless the intervening impedance is also correspondingly high. Mechanical interconnection of the regulators, use of "in-phase" regulators and "phase shifters" are means employed for correcting this fault.

Likewise, unless interconnected in some way, operation of any two regulators in parallel is likely to be unstable. With ordinary compensation, if the load starts up on one, its voltage increases and it takes more of the load while the other falls off in proportion. Stability may be maintained by electrical interconnection, using current from one line in the compensator for the other, or totalizing currents for all lines, etc.

Boosters.—Where low voltage is encountered, it may be corrected, temporarily at least, by use of transformer taps where such are available. In standard distribution transformers these are usually provided only with voltages, 6,600 volts or more, hence are not often available in general distribution work where lower voltages are used, unless taps are specially provided. The effect of using taps is to change the ratio of the transformer, for example, from 10 to 1 to 9 to 1. Hence, although they increase the full-load voltage, they increase the no-load voltage as well and therefore can be used only when the resulting increase in no-load voltage is endurable. They do not improve the regulation.

A similar result may be accomplished by the use of booster transformers. A booster is a transformer connected as an autotransformer in the primary line, serving to add a given percentage

permanently to the line voltage at that point Figures 112, 113, 114, and 115 show various connections of booster transformers.

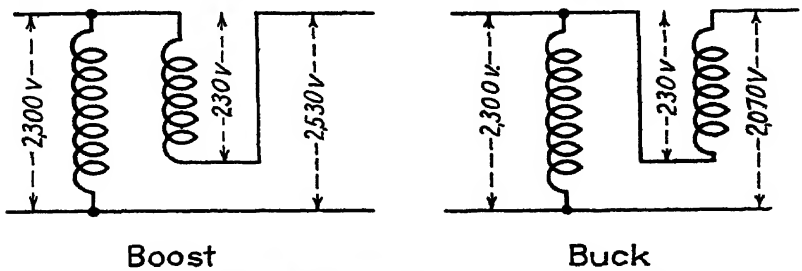


FIG 112 —Single-phase boost or buck connection.

The percentage boost depends on the ratio of voltages between primary and secondary coils of the transformer used. For example,

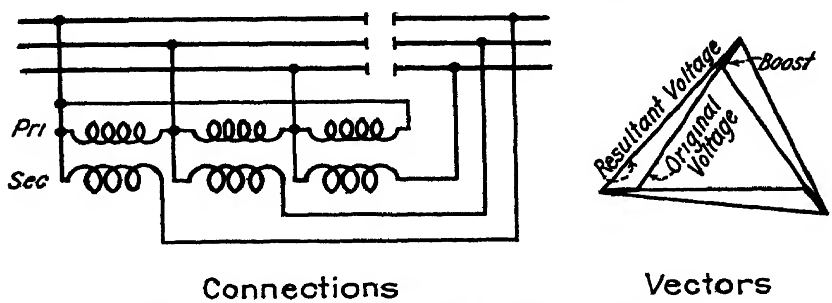


FIG. 113 —Three-phase boost, dealt connected

a 10 to 1 transformer will give a 10 per cent boost if connected as a single-phase boost. The capacity in kv-a necessary in the

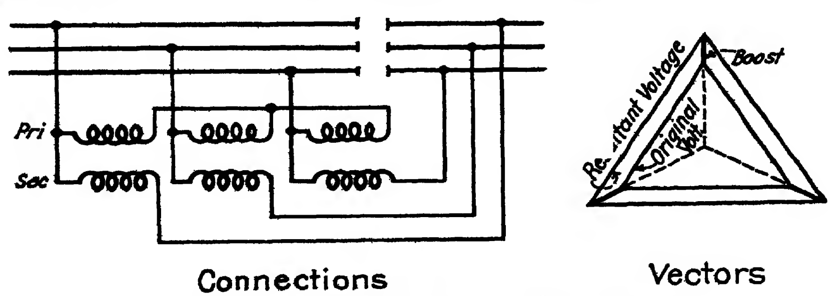


FIG. 114 —Three-phase boost, Y connected.

boost is determined by the current-carrying capacity of the secondary coil, through which full-load line current passes. For a 10 to 1 transformer on a single-phase line, for example, the secondary

current rating is ten times that of the primary. Hence ten times the full-rated kv-a. of the transformer may be carried or its capacity as a booster, not allowing for possible overload capacity, is ten times its normal rating. The capacity of such a transformer used as a booster should therefore be 10 per cent of the full-line load in kv-a. The per cent boosts and capacities may

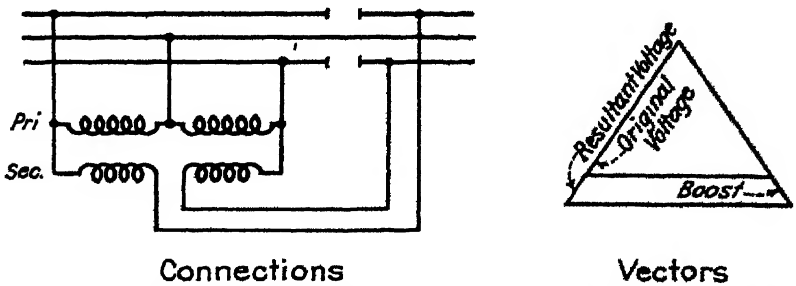


FIG. 115.—Three-phase boost with two single-phase transformers.

be similarly worked out for other connections, making due allowance for relative coil ratios, voltages, currents, etc. Table VII gives a summary of the more common booster connections with the corresponding per cent boosts and capacities in terms of line load.

High voltage may be lowered or bucked down in an exactly similar way by reversing transformer connections.

In connecting a boost or buck the polarity of the transformer is important (see Chap. IX). Most standard single-phase distribution transformers are of additive polarity, so that a booster action is attained if adjacent primary and secondary leads (a and c) are tied together as shown in Fig. 116. If (a) is tied to (d) and (c) to the line, a buck will result.

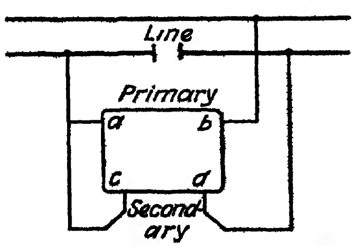


FIG. 116.—Connection of boost.

It should be noted that certain booster connections have the effect of changing the position of the phases, hence lines with such boosters cannot be paralleled with other lines with different booster connections or with none at all.

The boost is usually a more or less temporary expedient to raise the voltage until a more permanent means, such as additional line capacity, can be added, since where low voltage occurs, better regulation is usually desired rather than merely a raise in voltage.

Sometimes a boost is installed in connection with a regulator where the regulator is not able to maintain as high voltage as is desired and yet can serve to hold the no-load voltage down to suitable limits in opposition to the boost. For example, if the applied voltage were 120 at no load and dropped to 105 at full load and it were desired to have 120 volts at full load A 10 per cent regulator would give only 115 volts at full load, but if a 5 per cent boost were added, the full-load voltage would be raised to 120. The no-load voltage would be 125 without the regulator. The regulator could lower this, however, to as low as 115 if desired and could easily maintain a constant 120 volts.

TABLE VII —BOOSTER TRANSFORMER DATA

System	Transformer	Primary connection	Transformer ratio	Percentage voltage boost or buck	Total booster capacity in percentage of total line load, kv-a	
Single-phase			10.1	10 00	10	
			20 1	5 00	5	
			40 1	2 50	2 5	
Two-phase..	Same as single-phase					
Three-phase	Two single-phase		10·1	10 00	11 54	
			20 1	5 00	5 77	
			40 1	2 50	2 89	
	Three single-phase	Δ	10 1	15 28	17 33	
			20 1	7 56	8 66	
			40 1	3.80	4 33	
					Rated for Y voltage	Rated for Δ voltage
		Y	10·1	10.00	10 00	17 31
			20.1	5 00	5 00	8 66
			40 1	2.50	2 50	4 33
	Three-phase (Y-Δ coils)	Y	5 1	34.67	34 67	
			10 1	17.33	17 33	
			20 1	8.66	8 66	
			40·1	4 33	4.33	
	Three-phase (Δ-Δ coils)	Δ	10·1	15 28	17 33	
			20 1	7 56	8 66	
			40 1	3 80	4 33	

Computation of Voltage Drop.—Several methods for computing voltage drop are in common use in connection with problems on distribution systems, involving more or less approximation according to the nature of the problem and the accuracy desired. A few of the most useful will be given with their derivation.

Then their application to various types of circuits will be taken up.

For strictly accurate computation the following characteristics of a circuit should be considered:

1. Resistance of conductors.
2. Self-inductance of conductors
3. Mutual inductance between conductors.
4 Capacitance between conductors of circuits (or to neutral).
5. Leakage over insulation.
6. In some cases other factors such as mutual inductance from neighboring circuits, capacitance between conductors of circuit and other circuits, to ground, etc.

For high-voltage transmission circuits, especially if comparatively long, resistance, inductance, and capacitance between conductors are usually considered and, if considerable accuracy is desired, these are figured as distributed along the line. Leakage and the items listed above under (6) are ordinarily too small comparatively, on power circuits, to warrant inclusion.

When lower voltage circuits, especially those of relatively short length, are considered, the item of capacitance may usually be neglected without introducing any considerable error, since the capacitance is a shunt-circuit phenomenon (not in series) and enters the computations in the form of its effect in causing charging current. The charging current is directly proportional to the voltage and the length of the line, hence for lower voltages and short lengths such as are usually typical of distribution circuits (*i.e.*, voltages under 15,000 volts and lengths less than 50 miles), the effect of the charging current is insignificant. For such circuits it is generally sufficient to use only resistance and inductance of the circuit, both being series-circuit phenomena and hence of practically constant value per unit length of circuit along the line for a given size of conductor and configuration.

Simple Circuits.—For a circuit having *resistance only*, the voltage necessary to pass the current through the circuit is

$$e_r = IR$$

where

I = the current in amperes.
R = the resistance of the circuit in ohms.

This voltage is in phase with the current I.

For a circuit having *inductance* only, the voltage necessary to pass the current through the circuit is

$$e_x = IX$$

where

X = the inductive reactance of the circuit in ohms.

This voltage is ¼ cycle or 90 deg in advance of the current I.

For a circuit having *both resistance and inductance* the two voltages necessary to pass the current through them individually may be added directly (vectorially) since the two are in series. The resultant voltage is the total voltage necessary to pass the current through the circuit. In Fig. 117, IR is the resistance voltage in phase with the current I, IX is the reactance voltage, 90 deg. ahead of the current I. IZ is the vector sum of the two $IZ = \sqrt{(IR)^2 + (IX)^2} = I\sqrt{R^2 + X^2}$, the impedance voltage. Therefore the impedance $Z = \sqrt{R^2 + X^2}$.

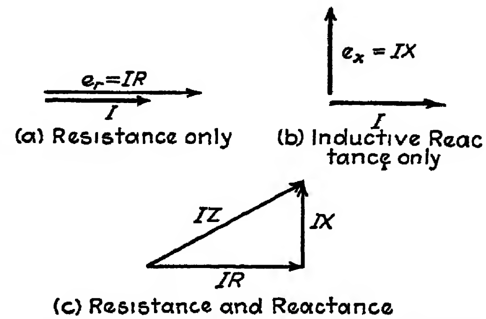


FIG 117—Voltage and current relations in circuits.

This impedance voltage IZ represents the voltage (in both magnitude and phase) necessary to pass the current I over a circuit consisting only of the resistance R and the inductive reactance X, such a circuit as is represented in Fig. 118. *It does not,* however, represent the voltage drop in a circuit with these characteristics but *carrying a load current,* such as the ordinary distribution circuit.

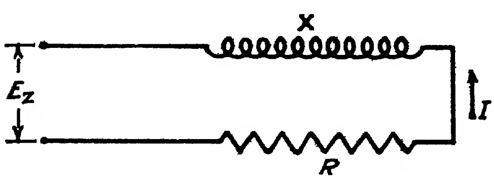


FIG. 118.—Impedance voltage

For convenience, assume a simple circuit with ground return, Fig. 119, the ground being assumed, for simplicity, to have no resistance or reactance in itself. E_1 is the voltage impressed at the source end of the line, E_2 the voltage at the receiver or load end, I the load current at power factor cos θ, R and X the resistance and inductive reactance of the line itself. Then the vector diagram in Fig. 119 shows the relation of voltages. To E_2

the receiver voltage, which is at an angle θ ahead of the load current I, is added vectorally IR the resistance voltage of the line in phase with I, and IX the reactance voltage if the line at 90

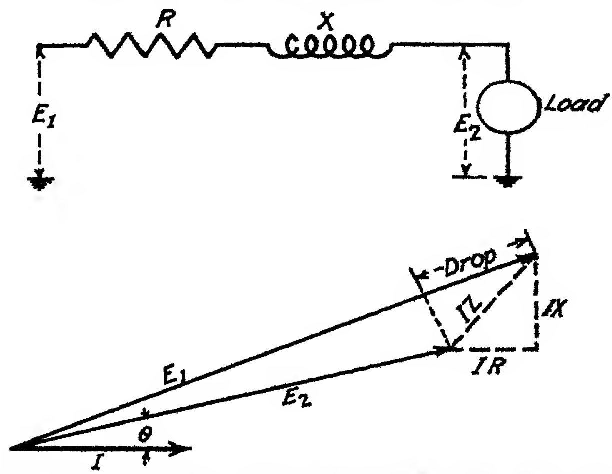


FIG. 119.—Voltage relations in circuit carrying load.

deg. ahead of I. The resultant, E_1, is the necessary voltage at the source in both magnitude and phase relation to I (and E_2).

The voltage drop in the line is numerically equal to $E_1 - E_2$ and may be quite different from IZ, the impedance voltage, as may be seen from Fig. 119.

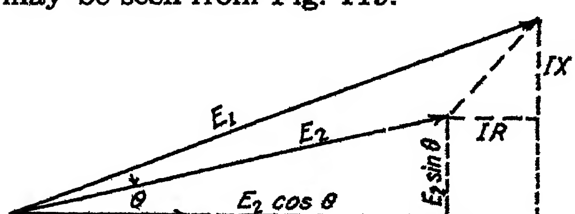


FIG. 120.—Illustrating computation of voltage drop using voltage at load.

Computing the above solution mathematically, E_2 may be resolved into two components at right angles to each other, see Fig. 120, *i.e.*

E_2 *cos* θ in phase with I (and with IR) and E_2 *sin* θ at 90 deg. ahead of I or in phase with IX. Then

$$(E_2 \cos \theta + IR)^2 + (E_2 \sin \theta + IX)^2 = E_1^2$$

or

$$E_1 = \sqrt{(E_2 \cos \theta + IR)^2 + (E_2 \sin \theta + IX)^2} \qquad (21)$$

and the voltage drop is

$$e = E_1 - E_2 = \sqrt{(E_2 \cos \theta + IR)^2 + (E_2 \sin \theta + IX)^2} - E_2 \qquad (22)$$

and in per cent of E_2.

$$V = \frac{\sqrt{(E_2 \cos\theta + IR)^2 + (E_2 \sin\theta + IX)^2} - E_2}{E_2} \times 100. \quad (23)$$

Similarly, starting with the voltage at the source E_1,

$$E_2 = \sqrt{(E_1 \cos\theta_1 - IR)^2 + (E_1 \sin\theta_1 - IX)^2} \quad (24)$$

$\cos\theta_1$ being the power factor at the source and not at the load in this case.

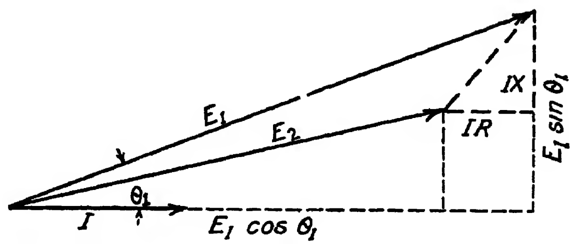


FIG. 121.—Illustrating computation of voltage drop using voltage at source.

These are fundamental equations for computing voltage drop when capacitance is neglected and are the basis of practically all charts and simplified formulæ.

Simplified Formula.—A great many of the ordinary voltage-drop problems of the distribution system may be solved conveniently by an approximation which is sufficiently accurate for most medium- or low-voltage circuits of comparatively short length and with single-phase or balanced polyphase loads. Referring to equations given above,

$$e = \sqrt{(E_2 \cos\theta + IR)^2 + (E_2 \sin\theta + IX)^2} - E_2.$$

Expanding

$$e = \sqrt{E_2^2 \cos^2\theta + 2E_2IR\cos\theta + I^2R^2 + E_2^2\sin^2\theta + 2E_2IX\sin\theta + I^2X^2} - E_2.$$

$$= \sqrt{E_2^2(\cos^2\theta + \sin^2\theta) + 2E_2I(R\cos\theta + X\sin\theta) + I^2(R^2 + X^2)} - E_2$$

$$= \sqrt{E_2^2 + 2E_2I(R\cos\theta + X\sin\theta) + I^2(R^2 + X^2)} - E_2.$$

If the last term under the radical were

$$R^2\cos^2\theta + 2RX\cos\theta\sin\theta + X^2\sin^2\theta$$

the whole expression under the radical would be the perfect square of

$$E_2 + I(R\cos\theta + X\sin\theta).$$

That is, the expression for voltage drop would become

$$e = I(R\cos\theta + X\sin\theta). \quad (25)$$

The error introduced by this approximation is only that due to subtracting $I^2(R \sin \theta - X \cos \theta)^2$ under the radical. This error is usually small. It is shown graphically in Fig. 122. This approximate formula may be simply stated as follows:

$$\text{Volts drop} = \frac{e}{I} = R \cos \theta + X \sin \theta. \qquad (26)$$

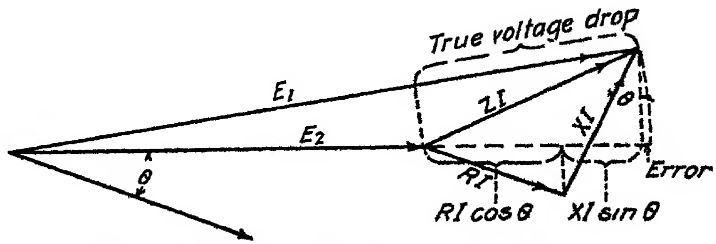


FIG. 122.—Illustrating approximate formula.

Complex Quantities.—While the algebraic method shown above is convenient for simple problems of voltage drop, it is very often necessary, especially with unbalanced loads and voltages on polyphase circuits and when dealing with several sections of a circuit with different characteristics, in series, to use an equivalent method employing complex quantities. Assume the simple

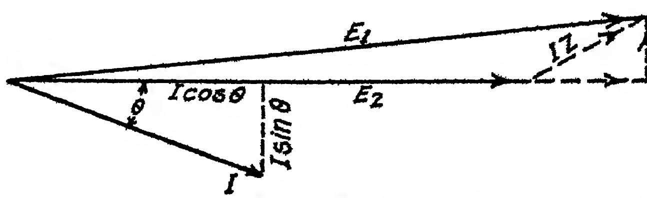


FIG. 123.—Complex quantity solution using voltage at load.

circuit as before. Let the voltage vector E be the reference base, Fig. 123. The current I expressed vectorially is

$$\dot{I} = I \cos \theta - jI \sin \theta.$$

The impedance of the circuit may be expressed as

$$\dot{Z} = R + jX.$$

The impedance drop in the circuit is therefore,

$$\begin{aligned} \dot{I}\dot{Z} &= (I \cos \theta - jI \sin \theta)(R + jX) \\ &= IR \cos \theta + IX \sin \theta + j(IX \cos \theta - IR \sin \theta). \qquad (27) \end{aligned}$$

This drop may be added to the voltage E as shown in Fig. 123. If that voltage and the corresponding power factor $\cos \theta$ are

assumed as delivered voltage E_2 and power factor, the result will be E_1, the voltage at the source

$$E_1 = E_2 + I(R \cos \theta + X \sin \theta) + jI(X \cos \theta - R \sin \theta). \quad (28)$$

Conversely, if E and θ are assumed as source voltage E_1 and power factor, the impedance drop must be subtracted to give receiver voltage, E_2

$$E_2 = E_1 - I(R \cos \theta + X \sin \theta) - jI(X \cos \theta - R \sin \theta). \quad (29)$$

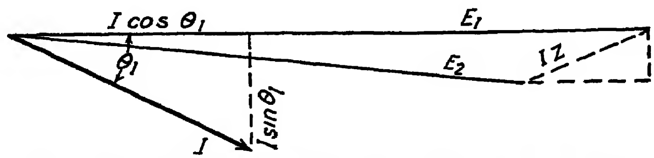


FIG 124 —Complex quantity solution using voltage at source

Direct Current.—Since inductance and phase relations do not enter into the computations with direct current, the voltage drop is simply that of a circuit containing resistance only.

$$e = RI$$
$$E_2 = E_1 - e.$$

It must be remembered in this connection that R is the resistance for the complete *circuit*, hence for a two-wire circuit, it includes the resistance of both the outgoing and the return wires.

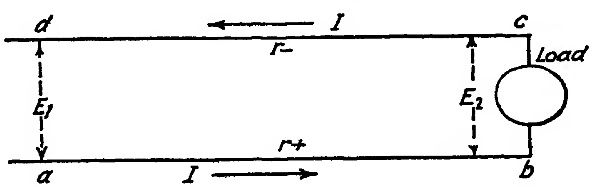


FIG. 125 —Direct-current, two-wire circuit

Consider the circuit shown in Fig. 125. Since the current in the + side flows from a to b there is a drop in potential of Ir_+ from a to b; similarly, there is also a drop of Ir_- from c to d. Hence, following around the complete circuit from a,

$$Ir_+ + E_2 + Ir_- = E_1,$$
$$E_2 = E_1 - I(r_+ + r_-) \text{ or if } r_+ = r_-;\ E_2 = E_1 - 2rI.$$

This is the ordinary *two-wire direct-current circuit.*

Consider now the circuit shown in Fig. 126 for the ordinary *three-wire Edison direct-current system.* Since the current in the + side flows from a to b there is a drop in potential of I_+r_+ in ab; similarly there is a drop of I_-r_- from c to d. In the neutral, however, the drop may be from e to f or from f to e depending on whether the neutral current flows from e to f or

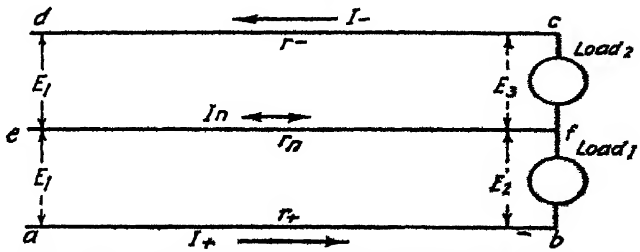


Fig. 126.—Direct-current, three-wire Edison circuit.

from f to e. This in turn depends on how the load is balanced between the two sides of the circuit. If load 1 is greater than load 2, I_+ will be greater than I_- and I_n (equal to $I_+ - I_-$) will flow from f to e. Hence, following around the circuit from a

$$I_+r_+ + E_2 + I_nr_n = E_1;\ E_2 = E_1 - I_+r_+ - I_nr_n,$$

and in the upper circuit,

$$-I_nr_n + E_3 + I_-r_- = E_1;\ E_3 = E_1 + I_nr_n - I_-r_-.$$

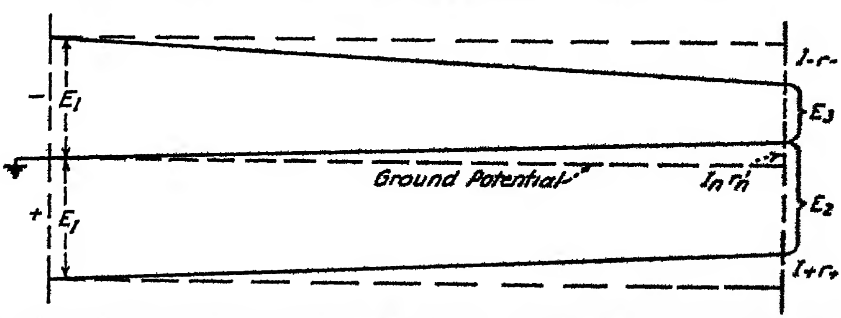


Fig. 127.—Direct-current, three-wire circuit—voltage with unbalanced load.

If the load is greatly unbalanced, I_+ being much larger than I_-, a condition may be reached where I_nr_n is larger than I_-r_- and E_3 is hence larger than E_1. That is, there is a rise in voltage on one side of the line. This is always the case for a totally unbalanced load on such a circuit since in this case I_- is 0. The result may be shown diagrammatically as in Fig. 127.

Single-phase Alternating-current Circuits.—The single-phase circuit is quite similar to the direct-current circuit except that the consideration of inductance in the circuit is introduced and also power factor of the load. A similar analysis of the two- and three-wire circuits may be made for single-phase alternating-current circuits as was made for the direct-current circuits, keeping these differences in mind.

The alternating-current, two-wire circuit may be conveniently considered as two circuits from phase wire to neutral (see Fig. 128), each with its phase-to-neutral voltage equal to one-half the line-to-line voltage. The resulting voltage drops in each of these circuits may be obtained by application of the fundamental formulæ given above for the simple circuit.

The drops thus obtained must be added together (vectorially) to obtain the total voltage drop of the circuit.

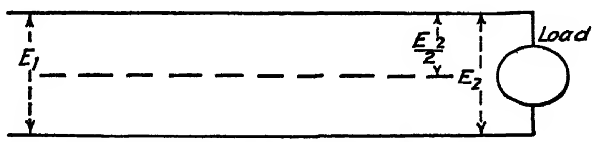


FIG 128—Alternating-current, single-phase, two-wire circuit

Of course, for the simple symmetrical circuit, the full voltage *between wires* may be used with the total length of the wire, giving the same results as above. The circuit-to-neutral method is given as it corresponds better with the method used for three-wire and polyphase circuits.

If drops are obtained in percentage of phase-to-neutral voltage, *i.e.*, $E_2/2$, the same percentage will apply to total drop and phase-to-phase voltage if the circuit is symmetrical, *i.e.*, with both conductors the same size.

Example.—Assume a circuit with 110 volts at the load, No. 4 copper conductors, 2 kw load at 90 per cent power factor, 800 ft. from source to load, conductors 14 in. apart, 60 cycles.

$r = 0.257$ ohm per 1,000 ft. $\quad R = 0.2056$ ohm per 800 ft.

$x = 0.1185$ ohm per 1,000 ft. $\quad X = 0.0948$ ohm per 800 ft.

$\cos\theta = 0.90 \quad \sin\theta = 0.436$

$E_2 = 110 \qquad \frac{E_2}{2} = 55$

$$I = \frac{2{,}000}{110 \times 0.90} = 20.2 \text{ amp.}$$

$$\begin{aligned} e &= \sqrt{(55 \times 0.9 + 20.2 \times 0.2056)^2 + (55 \times 0.436 + 20.2 \times 0.0948)^2} - 55 \\ &= \sqrt{(49.5 + 4.17)^2 + (24.0 + 1.92)^2} - 55 \\ &= \sqrt{53.67^2 + 25.92^2} - 55 = 59.6 - 55 = 4.6 \text{ volts in half the circuit} \end{aligned}$$

or from one side to neutral. Both sides are the same, hence the total drop $= 2 \times 4.6 = 9.2$ volts, *i.e.*, the voltage at the source must be $110 + 9.2 = 119.2$ volts In percentage,

$$\frac{4.6}{55} = 8.36 \text{ per cent.}$$

Using the approximate method,

$$\begin{aligned} e &= 20.2(0.2056 \times 0.9 + 0.0948 \times 0.436)2 \\ &= 40.4(0.185 + 0.0413) = 9.15 \text{ volts.} \end{aligned}$$

Similarly, the three-wire circuit (Fig. 129) may be considered as three separate circuits and the drop obtained for each. In this case, the middle wire has 0 voltage to neutral at the source and its

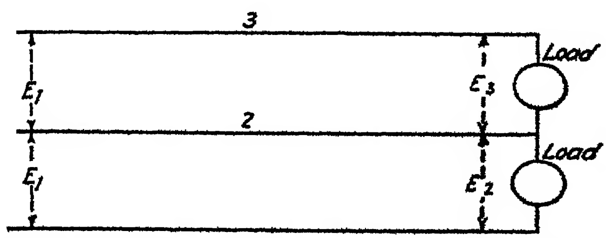


FIG. 129.—Alternating-current, single-phase, three-wire circuit.

voltage to neutral at the load will be equal to its line drop. This may be in the same sense as the drop in either phase wire, depending on which phase wire carries the heavier current (which side of the line has the heavier load). For example, if the greater load is across E_2, the current in the middle wire will be in the same sense as that in the wire No. 3, hence

$$\left.\begin{aligned} E_2 &= E_1 - \text{drop in } 1 - \text{drop in } 2 \\ E_3 &= E_1 + \text{drop in } 2 - \text{drop in } 3 \end{aligned}\right\} \text{vectorially.}$$

Percentage drops in this case must be applied separately for the two sides or across the outside ($2E_1$), the percentage being different if the load is unbalanced.

Example.—Assume similar conditions as for the example given for a two-wire circuit except assume the total load is 4 kw. divided so that 2.5 kw. is connected across 1–2 and 1.5 kw. across 2–3; all three wires No. 4.

From the approximate method, the volts drop per ampere $= \frac{9.15}{40.4} = 0.2263$.

Wire No 1 carries $\frac{2\ 5}{2} \times 20\ 2 = 25\ 25$ amp

Wire No. 2 carries $\frac{2\ 5 - 1\ 5}{2} \times 20\ 2 = 10\ 1$ amp.

Wire No 3 carries $\frac{1.5}{2} \times 20.2 = 15.15$ amp.

Drop in 1 = 25 25 × 0.2263 = 5.7 volts
Drop in 2 = 10 1 × 0 2263 = 2.3 volts
Drop in 3 = 15.15 × 0.2263 = 3.4 volts.

$E_2 = 5\ 7 + 2.3 = 8\ 0$ volts less than E_1.
$E_3 = 3.4 - 2\ 3 = 1.1$ volts less than E_1.

If E_1 is 115 volts on both sides of the circuit,

$$E_2 = 107;\ E_3 = 113\ 9$$

If considerable accuracy is required, the effect on the inductance of each wire of its distance from the other two wires and the division of load should be considered. That is, in the above example, 2 and 3 may be considered as the divided return circuit for 1, hence the inductive reactance of 1 should be that for a weighted average of its separation from 2 and from 3.

The diagram of Fig. 127 applies equally well to this problem as to a direct-current circuit for illustration. The computations may be considerably more complicated, however, if loads of different power factors are encountered on the two sides of the circuit or if different sized wires and different spacings are used.

It should be noted that if the neutral were grounded at both ends, the conditions are altered, in that both the neutral wire and ground then carry part of the unbalanced current.

Where the load is balanced or practically so, the middle wire may be neglected and the circuit figured as if it were a two-wire circuit at a voltage of $2E_1$. This is the method used for most general problems of single-phase circuits.

Two-phase Circuit.—The two-phase circuit may be analyzed into phase-to-neutral circuits or into separate single-phase circuits as may best fit the case. These may be solved in accordance with the principles given herewith for the simple circuit or the single-phase circuit.

The four-wire, two-phase circuit is essentially two separate single-phase circuits and may be readily treated as such.

In the three-wire circuit, Fig. 130, the third conductor carries the combined current of the other two, equal to the $\sqrt{2}$ times either one, for balanced load. The exact computation of voltage drop in this case is complicated by the distortion in the vector

relations of the voltage by the drop in the third wire as indicated in Fig. 130. Even with the balanced load shown, the resultant voltages AC and AB are unequal and not 90 deg. apart. (The figure is exaggerated, of course.) Probably the only satisfactory way of computing this accurately is by the complex-quantity method as given in some detail below for the three-phase circuit. For approximate results, however, the two phases may be computed as two separate single-phase circuits without introducing great error in most cases.

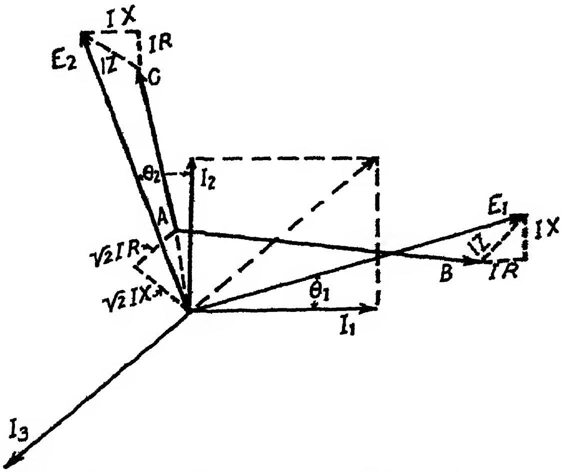


FIG. 130.—Voltage drop in two-phase, three-wire circuit.

The five-wire circuit, Fig. 131, if carrying balanced load, may also be considered as two-single phase circuits, neglecting the neutral, or as four separate circuits to neutral. If the load is unbalanced, however, and the neutral carries current, its drop must be considered. In such a case the complex-quantity method is available for obtaining accurate results. Otherwise, approximate results may be obtained by assuming an average balanced load.

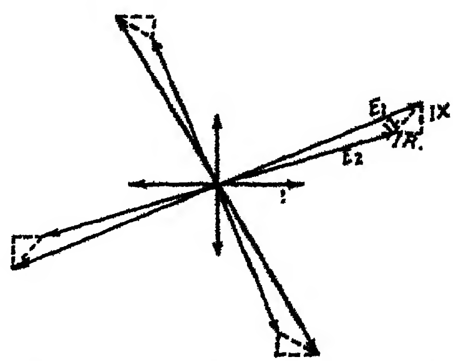


FIG. 131.—Voltage drop in two-phase, five-wire circuit.

Three-phase Circuit.—The three-phase circuit may be considered as three separate circuits to neutral, the drop in volts (or in per cent) being computed for each phase. The drop in per cent (for balanced load) will be the same for the phase-to-phase voltages as for the phase-to-neutral voltage. The drop in volts between two phases will be the vector sum of the drop in each phase-to-neutral circuit.

For a balanced three-phase system with balanced load the resultant drop between phases is equal to $\sqrt{3}$ times the drop in volts from any phase to neutral (the drop in all phases being equal). This is illustrated by Fig 132.

For unbalanced loads, the drop in each phase-to-neutral circuit will be of different magnitude and phase relation to the original voltage, hence the resultant can only be obtained by vectorial addition. Figure 133 shows a vector diagram of the voltages, currents, and voltage drops in a three-phase circuit with unbalanced load but with no neutral current (three-wire system). In this case the currents in the three phases must sum up to zero.

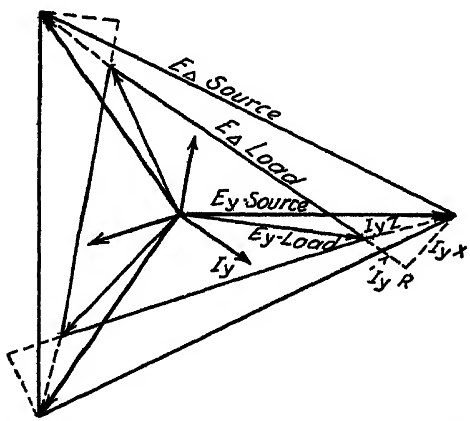


FIG 132.—Voltage drop in three-phase circuit, balanced load.

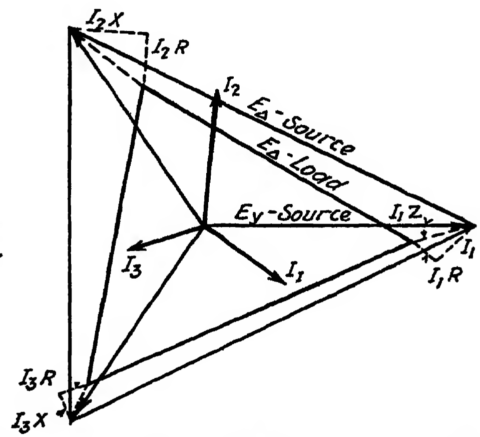


FIG. 133—Voltage drop in three-phase, three-wire circuit, unbalanced load.

Where there is a neutral, or fourth wire, it will also have a current and a voltage drop to neutral if the load is not balanced. This may be also computed as a phase-to-neutral circuit, the current being assumed in its proper phase relation to the other phase currents, and the resultant voltage to neutral obtained Figure 134 shows a vector diagram of the voltage drop produced in the neutral of a four-wire, three-phase system where the neutral carries an appreciable current. This current is equal to the vector sum of the currents in the three phases.

Where the neutral is grounded at the load end as well as the source, the ground will carry part of the unbalanced current and the neutral wire part. This must be considered in computing the drop in the neutral. It is sometimes assumed that all the current

is carried by ground but this is not true if there is a fourth wire of good conductivity, since the ground connections have appreciable impedance. The effect of the drop in the neutral is, of course, to shift the neutral point somewhat and change the voltage from each phase to neutral correspondingly.

In some cases, the voltage at the load may be assumed and the voltage at the source computed from it. This is often convenient since it is usually desired to maintain a certain voltage at the load. The problems might just as well be figured starting with a balanced

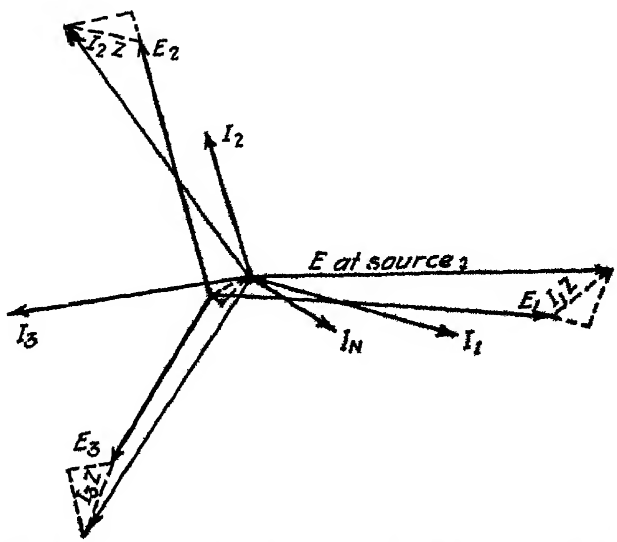


FIG. 134.—Voltage drop in three-phase, four-wire circuit, unbalanced load.

voltage at the source, however, and subtracting from it the drops in the various phases. The drop in the neutral is perhaps somewhat better represented in that way. Whichever way is assumed, the results obtained in drop in percentage will usually be not far different and for practical purposes, whichever way is most convenient, is satisfactory.

Example of Three-phase Circuit.—Assume a 4,000-volt, three-phase circuit, with No. 0 copper conductor, 1,000 kw. load at 80 per cent power factor, balanced on the three phases, 5,000 ft. from source to load, conductors 14 in. apart, 60 cycles.

r = 0.103 ohm per 1,000 ft.; R = 0.515 ohm for 5,000 ft.
x = 0.112 ohm per 1,000 ft. (17.6 in. equivalent spacing); X = 0.560 ohm for 5,000 ft.

$E_2 = 4{,}000$ volts; $\dfrac{E_2}{\sqrt{3}} = 2{,}300$ volts to neutral

$\cos\theta = 0.80$; $\sin\theta = 0.60$.

$$I = \frac{1{,}000{,}000}{\sqrt{3} \times 4{,}000 \times 8} = 180 \text{ amp. in each line wire.}$$

$$\begin{aligned} e &= \sqrt{(2{,}300 \times 0.8 + 180 \times 0.515)^2 + (2{,}300 \times 0.6 + 180 \times 0.560)^2} - 2{,}300 \\ &= \sqrt{(1{,}840 + 92.7)^2 + (1{,}380 + 100.8)^2} - 2{,}300 \\ &= \sqrt{1{,}932.7^2 + 1{,}480.8^2} - 2{,}300 = 2{,}434.8 - 2{,}300 \\ &= 134.8 \text{ volts drop in each wire.} \end{aligned}$$

$$\frac{134.8}{2{,}300} = 5.86 \text{ per cent drop.}$$

Since the load is balanced on the three phases in both amount and power factor, the voltages at both source and load are balanced, and the per cent drop figured for each phase-to-neutral applies also to phase-to-phase voltages.

Drop in volts across each phase = 5.86 per cent of 4,000 = 234.4 volts.

Voltage at source = 4,234.4 volts for a voltage of 4,000 at the load.

In most ordinary problems involving three-phase circuits it is sufficient to assume balanced load, as the computation is much simplified thereby. Even if the load is somewhat unbalanced, unless great accuracy is desired, the assumption of a balanced load equal to the average on the three phases will generally give results accurate enough for practical purposes. If, however, it is desired to study the unbalanced condition more carefully with its effect in unbalancing the voltage, etc., a more accurate method is necessary.

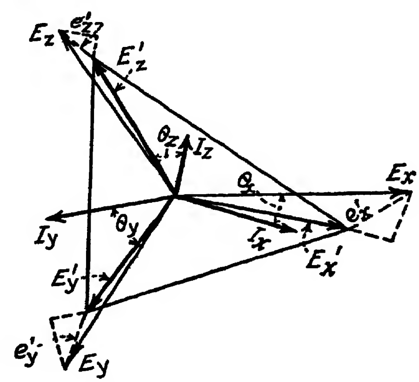


FIG. 135.—Voltage drop in three-phase, three-wire circuit, unbalanced load, solution by complex quantities.

Complex-quantity Method for Unbalanced Conditions.—When the load is not equally balanced on the three phases, the use of the complex-quantity method of analyzing the problem is probably the simplest, as any attempt at solution by the algebraic method is likely to be rather involved and must be carried out in a similar way.

For such a problem it is simpler to refer all phase-to-neutral currents and voltages to one of the phase-to-neutral voltages as a common base vector. In Fig. 135 a typical example is shown. In this case, the voltages and currents at the source are assumed as known and the resultant voltages at the load determined from them.

Let E_x be the base vector chosen. Assume balanced three-phase voltage at the source, E_x, E_y, E_z (to neutral) and E_{x-y}, E_{y-z}, and E_{z-x}, phase-to-phase.

The current I referred to E becomes,

$$\dot{I}_x = I_x(\cos\theta_x - j\sin\theta_x)$$
$$\dot{E}_x = E_x + j0.$$

The current I_y referred to E_y becomes,

$$\dot{I}_y = I_y(\cos\theta_y - j\sin\theta_y),$$

but E_y referred to E_x is

$$\dot{E}_y = E_y(\cos 240^\circ + j\sin 240^\circ)$$
$$= E_y\left(-0.5 - j\frac{\sqrt{3}}{2}\right). \tag{30}$$

If the voltage is not balanced, cos θ and sin θ for the proper angle between E_x and E_y may be used instead of cos 240 deg. and sin 240 deg.

Therefore, I_y referred to E_x is

$$\dot{I}_y = I_y(\cos\theta_y - j\sin\theta_y)\left(-0.5 - j\frac{\sqrt{3}}{2}\right)$$
$$= I_y\left(-0.5\cos\theta_y - \frac{\sqrt{3}}{2}\sin\theta_y + j0.5\sin\theta_y - j\frac{\sqrt{3}}{2}\cos\theta_y\right). \tag{31}$$

Similarly,

$$\dot{I}_z = E_z(\cos 120^\circ + j\sin 120^\circ)$$
$$= E_z\left(-0.5 + j\frac{\sqrt{3}}{2}\right). \tag{32}$$

$$\dot{I}_z = I_z\left(-0.5\cos\theta_z + \frac{\sqrt{3}}{2}\sin\theta_z + j0.5\sin\theta_z + j\frac{\sqrt{3}}{2}\cos\theta_z\right). \tag{33}$$

Impedance voltages may now be computed by multiplying each of the current vectors by its corresponding impedance $(R + jX)$. The results of these multiplications are voltage vectors referred to E_x as a base. If each of these is then subtracted from its corresponding original voltage (E_x, E_y, E_z), the resultant voltages at the load are obtained, each referred to E_x. Impedance drop, in X,

$$e_x' = \dot{I}_x(R_x + jX_x) = I_x(\cos\theta_x - j\sin\theta_x)(R_x + jX_x)$$
$$= I_x[R_x\cos\theta_x + X_x\sin\theta_x + j(X_x\cos\theta_x - R_x\sin\theta_x)]. \tag{34}$$

$$\dot{E}_x' = \dot{E}_x - e_x = E_x - I_x[R_x\cos\theta_x + X_x\sin\theta_x + j(X_x\cos\theta_x - R_x\sin\theta_x)]. \tag{35}$$

Impedance drop in Y,

$$e_y' = \dot{I}_y(R_y + jX_y) = I_y\left[-0.5\cos\theta_y - \frac{\sqrt{3}}{2}\sin\theta_y + j\left(0.5\sin\theta_y - \frac{\sqrt{3}}{2}\cos\theta_y\right)\right](R_y + jX_y)$$

$$= I_y\left[\left(-0.5R_y + \frac{\sqrt{3}}{2}X_y\right)\cos\theta_y - \left(\frac{\sqrt{3}}{2}R_y + 0.5X_y\right)\sin\theta_y + j\left(0.5R_y - \frac{\sqrt{3}}{2}X_y\right)\sin\theta_y + j\left(-\frac{\sqrt{3}}{2}R_y - 0.5X_y\right)\cos\theta_y\right]. \quad (36)$$

$$\dot{E}_y' = \dot{E}_y - e_y' = E_y\left(-0.5 - j\frac{\sqrt{3}}{2}\right) - \dot{e}_y' \text{ (as above).} \quad (37)$$

Impedance drop in Z,

$$e_z' = \dot{I}_z(R_z + jX_z)$$

$$= I_z\left[\left(-0.5R_z - \frac{\sqrt{3}}{2}X_z\right)\cos\theta_z + \left(\frac{\sqrt{3}}{2}R_z - 0.5X_z\right)\sin\theta_z + j\left(0.5R_z + \frac{\sqrt{3}}{2}X_z\right)\sin\theta_z + j\left(\frac{\sqrt{3}}{2}R_z - 0.5X_z\right)\cos\theta_z\right] \quad (38)$$

$$\dot{E}_z' = \dot{E}_z - \dot{e}_z' = E_z\left(-0.5 + j\frac{\sqrt{3}}{2}\right) - e_z' \text{ (as above).} \quad (39)$$

These expressions appear somewhat involved but are quite simple of solution, requiring only the insertion of the known constants. Each expression then reduces to a simple complex quantity of the form $K_1 + jK_2$ in which K_1 and K_2 are numerical quantities. The final solution for evaluating the voltage at the load in any case is then simply $\sqrt{K_1^2 + K_2^2}$.

The phase-to-phase voltages are quite easily deduced from these expressions for the phase-to-neutral voltages.

For the voltages at the source,

$$\dot{E}_{xy} = \dot{E}_x - \dot{E}_y = E_x + j0 - E_y\left(-0.5 - j\frac{\sqrt{3}}{2}\right)$$

$$= E_x + 0.5E_y + j\frac{\sqrt{3}}{2}E_y. \quad (40)$$

$$\dot{E}_{yz} = \dot{E}_y - \dot{E}_z = E_y\left(-0.5 - j\frac{\sqrt{3}}{2}\right) - E_z\left(-0.5 + j\frac{\sqrt{3}}{2}\right)$$

$$= -0.5(E_y - E_z) - j\frac{\sqrt{3}}{2}(E_y + E_z). \quad (41)$$

$$\dot{E}_{zx} = \dot{E}_z - \dot{E}_x = E_z\left(-0.5 + j\frac{\sqrt{3}}{2}\right) - E_x - j0$$

$$= -0.5E_z - E_x + j\frac{\sqrt{3}}{2}E_z. \tag{42}$$

Similarly,

$$\left.\begin{aligned} \dot{E}'_{xy} &= \dot{E}'_x - \dot{E}'_y \\ \dot{E}'_{yz} &= \dot{E}'_y - \dot{E}'_z \\ \dot{E}'_{zx} &= \dot{E}'_z - \dot{E}'_x \end{aligned}\right\}$$ Using the expressions for $\dot{E}_x'$, $\dot{E}_y'$, and $\dot{E}_z'$, as worked out from the equations given above.

These expressions worked out and evaluated give the voltages between phases for both source and receiver. The numerical difference ($E_{xy} - E'_{xy}$, for example) gives the voltage drop in volts. From these expressions may also be derived the change in phase position of any voltage between source and load and also the phase relations between voltages at the load.

Naturally this method being more cumbersome should be used only where the nature of the problem is such that phase-to-phase voltages are required and of such accuracy that an approximation using balanced loads and voltages of average values is not satisfactory.

Example.—Assume a problem similar to that given for balanced three-phase, except that the load instead of being 180 amp. in each phase is 187 amp. in phase X, at power factor 0.67, 150 amp. in phase y at power factor 0.85, and 210 amp. in phase z at power factor 0.85.

R = 0.515 ohm for 5,000 ft. of No. 0.

X = 0.560 ohm for 5,000 ft. of No. 0 at 17.6 in. equivalent spacing.

E = 4,000 volts at source; $\frac{E}{\sqrt{3}} = 2{,}300$.

$I_x = 187 \qquad \cos\theta_x = 0.67 \qquad \sin\theta_x = 0.74.$

$I_y = 150 \qquad \cos\theta_y = 0.85 \qquad \sin\theta_y = 0.527.$

$I_z = 210 \qquad \cos\theta_z = 0.85 \qquad \sin\theta_z = 0.527.$

$\dot{I}_x = 187(0.67 - j0.74).$

$$\dot{I}_y = 150\left(-0.5 \times 0.85 - \frac{\sqrt{3}}{2} \times 0.527 + j0.5 \times 0.527 - j\frac{\sqrt{3}}{2} \times 0.85\right)$$

$$= 150(-0.425 - 0.456 + j0.263 - j0.736) = 150(-0.881 - j0.473).$$

$$\dot{I}_z = 210(-0.425 + 0.456 + j0.263 + j0.736) = 210(0.031 + j0.999).$$

$\dot{E}_x = 2{,}300 + j0.$

$\dot{E}_y = 2{,}300(-0.5 - j0.866).$

$\dot{E}_z = 2{,}300(-0.5 + j0.866).$

$$\dot{e}_x' = 187(0.67 - j0.74)(0.515 + j0.560) = 187(0.759 - j0.006)$$
$$= 141.93 - j1.12.$$

$$e_y' = 150(-0.881 - j0.473)(0.515 + j0.560) = 150(-0.189 - j0.737)$$
$$= -28.35 - j110.55.$$

$$
\begin{aligned}
e_z' &= 210(0.031 + j0.999)(0.515 + j0.560) = 210(-0.543 + j0.531)\\
&= -114.03 + j111.51\\
\dot{E}_x' &= 2{,}300 + j0 - (141.93 - j1.12) = 2{,}158.07 + j1.12.\\
\dot{E}_y' &= -1{,}150 - j1{,}991.8 - (28.35 - j110.55) = -1{,}178.35 - j1{,}881.25.\\
\dot{E}_z' &= -1{,}150 + j1{,}991.8 - (-114.03 + j111.51)\\
&= -1{,}035.97 + j1{,}880.29.\\
\dot{E}'_{x-y} &= 2{,}158.07 + j1.12 - (-1{,}178.35 - j1{,}881.25)\\
&= 3{,}336.42 + j1{,}882.37.\\
\dot{E}'_{y-z} &= -1{,}178.35 - j1{,}881.25 - (-1{,}035.97 + j1{,}880.29)\\
&= -142.38 - j3{,}761.54.\\
\dot{E}'_{z-x} &= -1{,}035.97 + 1{,}880.29 - (2{,}158.07 + j1.12)\\
&= -3{,}194.04 + j1{,}879.17.
\end{aligned}
$$

The evaluation of these expressions is readily made and gives the numerical value of the voltages at the load. Figure 136 shows an approximate plotting of these vectors indicating their relative size and direction.

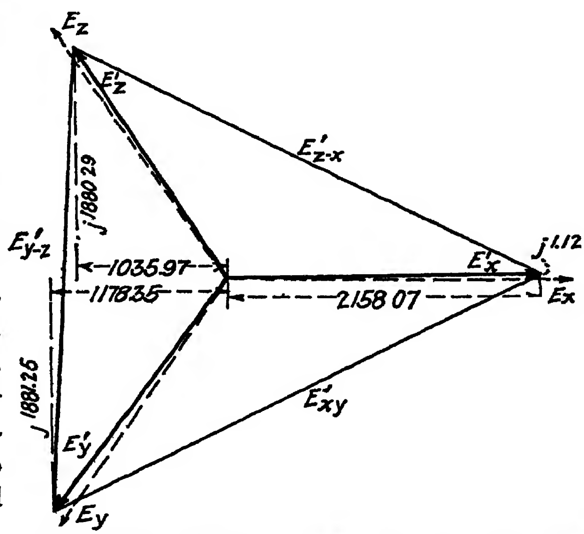


FIG. 136.—Example of solution by complex quantities

Drop in Neutral.—The voltage drop in the fourth wire or neutral, if such is present, can be set up in the same manner as shown for drop in the other three wires. That is, the current in the neutral may be expressed as a complex number referred to $\dot{E}_x$ as a base, multiplied by its proper $R + jX$, and the result evaluated. In this case, the phase-to-neutral voltages at the load must be determined by a vectorial combination of the neutral drop thus found and the drop in each phase, respectively, since the effect of the drop in the neutral is to shift that neutral somewhat with respect to the phase voltages.

Voltage Drop in Transformers.—In Chap. IX the question of equivalent resistance, reactance, and impedance for any transformer is discussed at some length. These quantities may be used in determining the equivalent voltage drop through the transformer considering the transformer as a single equivalent

circuit at either primary or secondary voltage as desired. For computing the voltage drop the simple approximate method given here will be found very convenient and usually sufficiently accurate for the general run of problems.

$$\frac{e}{I} = R \cos \theta + X \sin \theta.$$

It should be remembered that R and X referred to the primary side are n^2 times as large as when referred to the secondary side, n being the transformer ratio. Also, in three-phase installations R and X to neutral are three times their value from phase to phase (see Chap. IX).

Figure 137 illustrates a convenient form of chart for transformer regulation.

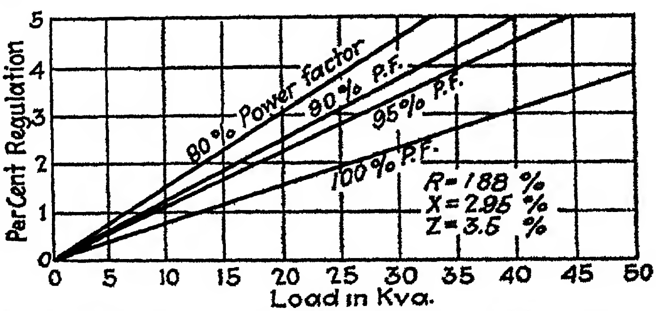


FIG. 137.—Typical regulation curves for 25-kv-a., single-phase, distribution transformer.

Delta-delta Banks.—The equations for the solution of current division and voltage drops in delta-delta banks of transformers carrying unbalanced loads was given in Chap. IX. The full method of developing these will not be given here but the general method of attack will be stated briefly. Loads are subdivided into single-phase components applied across each phase (delta currents). These currents are expressed as complex quantities referred to one phase-to-phase voltage as a base. The division of each current between the two paths of the delta (see Chap. IX) is determined by application of the theory of two impedances in parallel. The total current in any phase of the delta is then obtained by vector summation of the various components of current passing through that phase. The voltage drop is determined by multiplying this current by its proper $R + jX$ for the transformer. The complex quantity method is used

throughout following, in general, somewhat the same procedure as given above in detail for the unbalanced three-phase circuit. The general equations for this solution have been simplified and assembled and are given in Chap. IX.

Uniformly Distributed Load.—In all the above discussion of various voltage drop computations it has been assumed that the load was concentrated at the end of the line. It very often happens, in problems dealing with secondaries for example, that the load is distributed along the line for a certain distance, either in a definite number of individual locations or in such a manner that it may be considered as uniformly distributed.

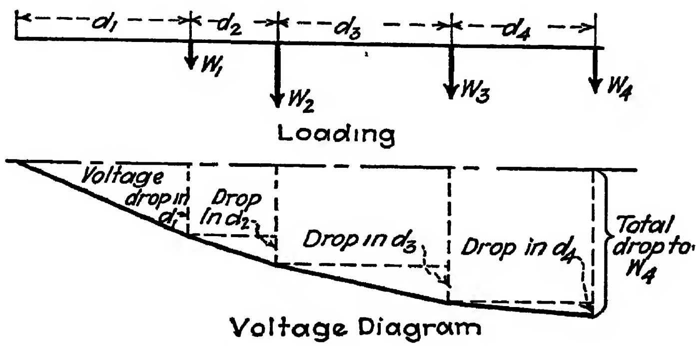


FIG. 138—Load distributed at definite points.

The latter case is simpler to deal with and sufficiently accurate for most ordinary problems.

For the first case, illustrated in Fig. 138, the drop is figured for each section of the line and the results added together to give the total drop, *i.e.*,

Drop of $W_1 + W_2 + W_3 + W_4$ over length d_1
$+$drop of $W_2 + W_3 + W_4$ over length d_2
$+$drop of $W_3 + W_4$ over length d_3
$+$drop of W_4 over length d_4
gives total drop to W_4.

If differences exist in the characteristics of the various loads and sections of line, the addition must be vectorial to be accurate.

Where the load may be assumed to be uniformly distributed, voltage drop may be computed by assuming the *total load* concentrated at the *midpoint* of the length over which it is dis-

tributed. Figure 139 illustrates the distribution of such a load and the resulting voltage drop at any point along the line. This assumption can be proved correct mathematically as follows:

The load at any point along the line is equal to

$$wl - wx$$

where

w = the load per unit length.
l = the total length.
x = the distance of the point in question from the source end of the line.

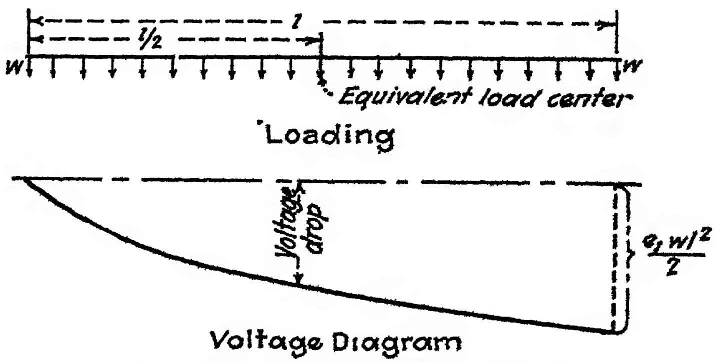


FIG. 139.—Uniformly distributed load.

The voltage drop over any increment length dx is

$$e_1(wl - wx)dx,$$

where

e_1 = the drop per unit load per unit length of line, which is constant.

Then the total drop of any point x is

$$\int_0^x e_1(wl - wx)dx = e_1\left(wlx - \frac{wx^2}{2}\right).$$

If $x = l$, the total length of the line,

$$\text{total drop} = e_1\left(wl^2 - \frac{wl^2}{2}\right) = e_1\frac{wl^2}{2},$$

which is evidently the drop which would be occasioned by the total load wl over one-half the total length, $l/2$.

Example.—Assume a balanced single-phase load density of 10 kw. per 1,000 ft on a 3 No 4 secondary extending 600 ft. from the transformer. Power factor 0 95; voltage at transformer $^{240}/_{120}$ volts; spacing between wires 8 in. — 8 in By the approximate method, assuming the total load of $\frac{600}{1,000} \times 10 = 6$ kw. concentrated at a distance of $\frac{1}{2} \times 600 = 300$ ft from the transformer.

$$r = 0.257 \text{ ohm per } 1,000 \text{ ft}, \; R = 0.077 \text{ ohm for } 300 \text{ ft.}$$
$$x = 0.122 \text{ ohm per } 1,000 \text{ ft}; \; X = 0.037 \text{ ohm for } 300 \text{ ft.}$$
$$I = \frac{6,000}{240 \times 0.95} = 26.3 \text{ amp}$$
$$e = (R \cos \theta + X \sin \theta)I = (0.077 \times 0.95 + 0.037 \times 0.311)26.3$$
$$= 2.22 \text{ volts per wire.}$$

Voltage at end of secondary = 120 − 2.22 = 117.78 volts to neutral or 235.56 volts between outside wires

Charts.—A great many charts for the easy computation of voltage drops have been published at various times and some of these are very useful. The practicability of such a chart depends upon two very important factors, (1) the user's familiarity with the chart and its method of operation; (2) the user's knowledge of its derivation and hence its limitations, for most of such charts are more or less limited in their application.

The accompanying charts are presented, not as the best necessarily, but as some which have been found useful on account of their fundamental character and simplicity of operation. In general, only simple slide-rule manipulation is required for the solution of any problem after the proper constants have been picked from the charts. It will usually be found that charts which are intended to give voltage drops directly without supplementary computation are either only very approximate in their accuracy, limited to a narrow range of problems, or quite complicated in their operation.

For the occasional problem, these charts will be found useful in their present general form, with the necessary additional calculations. Where a number of similar problems are to be solved, however, with certain quantities such as voltage or wire size fixed, it will sometimes be found convenient to make up special charts to fit the case, these being simplified by the elimination of some of the quantities which are variable in the general problem. For deriving these special charts these general charts can be used to good advantage. Figures 140 and 141 show examples of such special charts.

Charts Based on Long Formula.—The charts given in Figs. 142 and 143 are based on the formula given in equation (22) for the computation of voltage drop,

$$e = \sqrt{(E_2 \cos \theta + IR)^2 + (E_2 \sin \theta + IX)^2} - E_2.$$

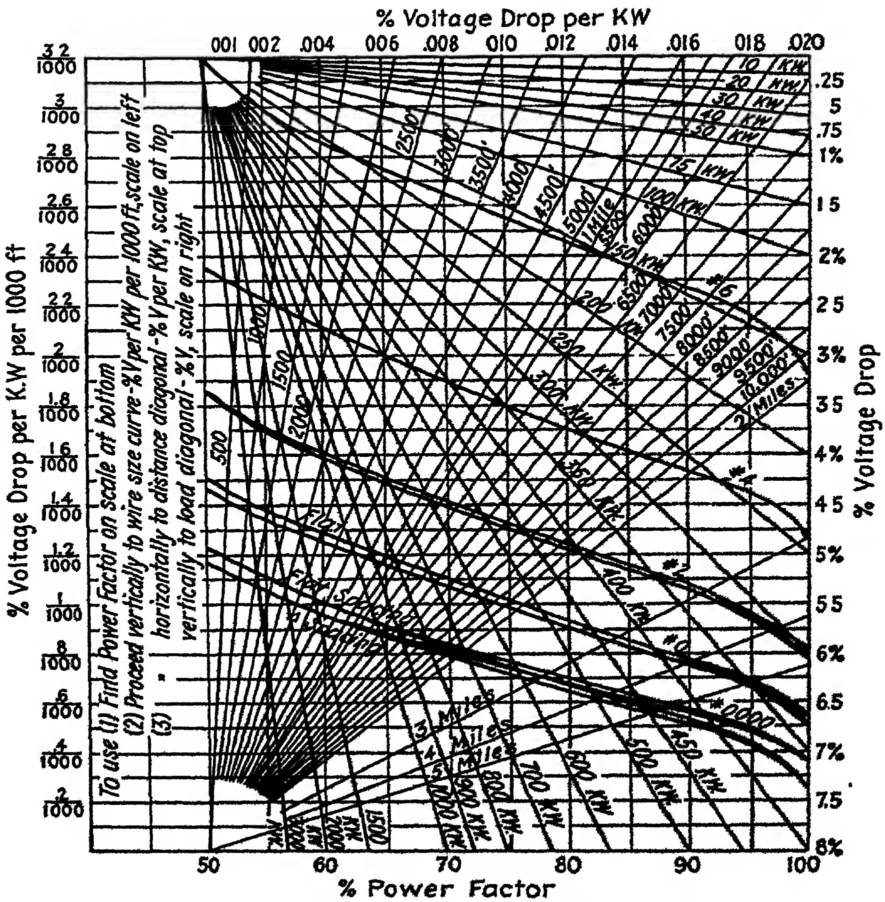


FIG. 140.—Voltage drop curves for 4,600 volt, 70 cycle, three-phase, lines. (For single phase, multiply scale readings by 2.)

An expansion of this expression leads to the development of a semi-constant which is designated as B. This quantity expresses the relationship between percentage of power loss and percentage of voltage drop in a circuit, as follows:

$$V = BP$$

where

V = per cent voltage drop
P = per cent power loss

$$B = \frac{\cos\theta}{p}\left(\sqrt{(1+p)^2 + \left(\tan\theta \pm p\frac{X}{R}\right)^2} - \frac{1}{\cos\theta}\right), \quad (43)$$

where

$$p = \frac{P}{100}$$

Use + for lagging power factor, − for leading.

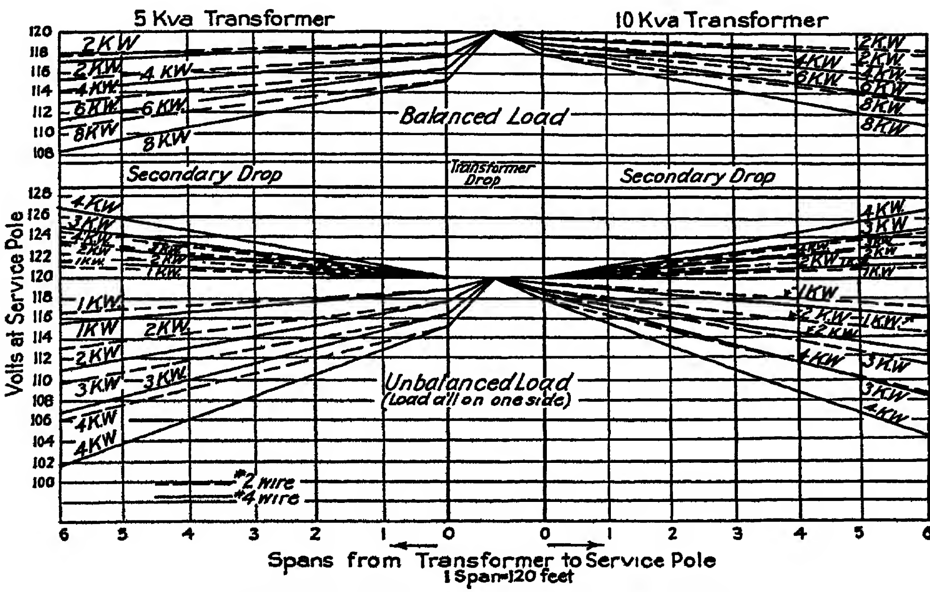


FIG. 141.—Voltage curves for range loads.

It will be noted that B depends not only on the relation between X and R in the circuit (X/R) and on the power factor of the load, but also to some extent on the value of P. That is why it is called a "semi-constant." The effect of P is negligible, however, through a considerable range of problems as shown by the curves on the chart.

Power loss is obtained from the expression

$$P = \frac{100WrD}{E^2\cos^2\theta} \text{ in per cent of } W\text{, the delivered power in watts.} \quad (44)$$

r = the resistance per unit length, D the length of the line

This expression is for balanced three-phase or two-phase circuits. For single-phase circuits the per cent power loss is twice this amount. The equation may be developed into the form,

$$\frac{P}{\text{kw.}\,\dfrac{D}{1{,}000}} = \frac{10^8 r}{(E \cos \theta)^2}, \tag{45}$$

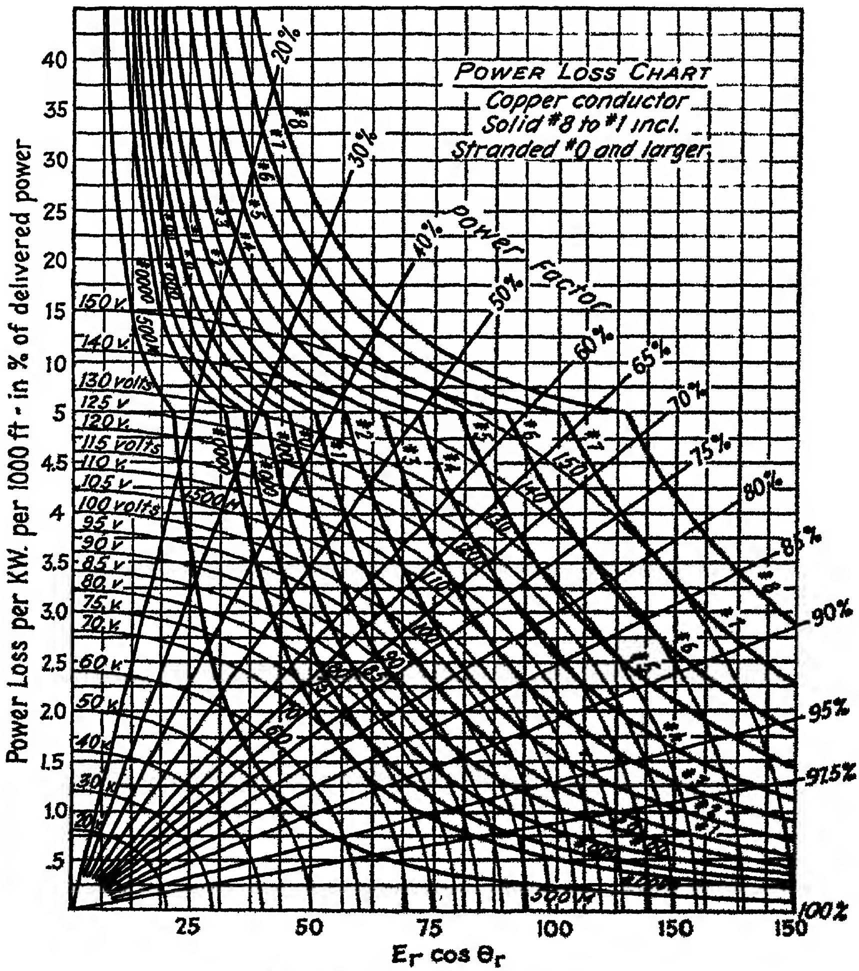


Fig. 142.—Power loss chart.

which may be plotted for any given wire size (r fixed) in terms of $\dfrac{P}{\text{kw.}\,\dfrac{D}{1{,}000}}$, the percent power loss per kilowatt per 1,000 ft.,

and $E\cos\theta$. This equation is plotted on Fig 142 for various standard sizes of conductor and using voltages between 0 and 150. Higher voltages can be brought within the scale of the

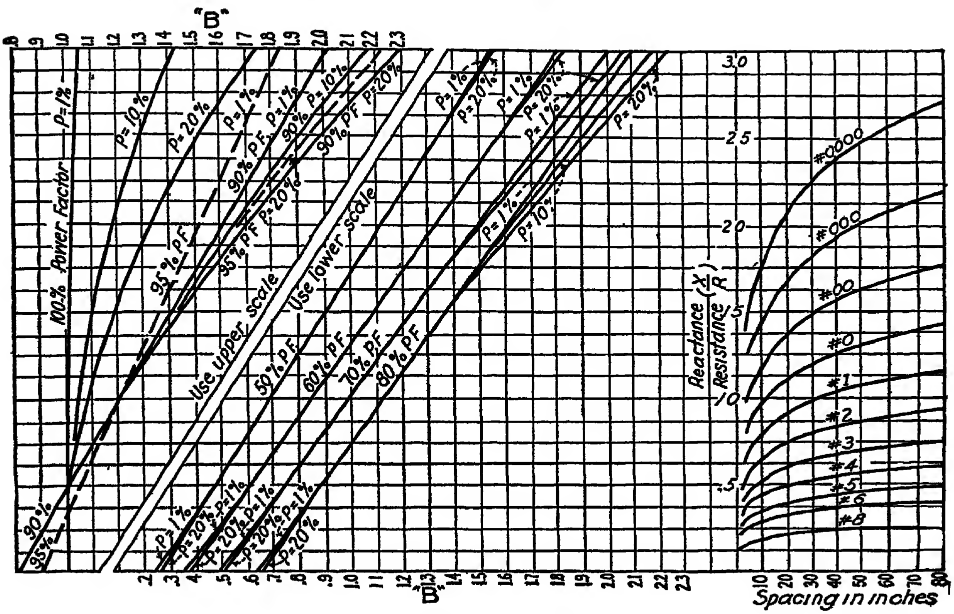


FIG. 143.—*B* chart.

$V = BP$; V = Per cent Voltage Drop; P = Per cent Power Loss. Drawn for copper wire at 60 cycles. For 25 cycles use $5/12 = .417$ times values given by scale for $\frac{X}{R}$.

chart by dividing by a convenient factor, 2, 4, 10, etc. The per cent power loss obtained from the chart is then corrected to the original voltage by dividing it by the square of the factor used (2^2, 4^2, 10^2, etc.). The quantity $E\cos\theta$ is solved graphically on the chart by the use of voltage circle (E) and power-factor diagonals ($\cos\theta$). The intersection of the circle through the proper voltage and the power-factor diagonal locates the ordinate corresponding to $E\cos\theta$.

The chart is plotted for three-phase (or two-phase) circuits. For single-phase, multiply the results obtained by 2.

The *B* chart, Fig. 143, is derived from the formula given above and is plotted for various ordinary lagging power factors and for a range in values of P. The supplementary chart on the right gives a graphical solution for the value of X/R for various

standard wire sizes and spacings, with 60-cycle frequency used in obtaining X. If a 25-cycle frequency is used, take 0.417 times the value of X/R as shown by this chart.

Use of Chart.

1. Divide actual voltage by a convenient factor to reduce it to the scale of the power-loss chart.

Example.—2,200 volts—divide by 20, 2,200/20 = 110.

2. Locate intersection of voltage arc and power-factor diagonal.

Example —110-volt arc, 85 per cent power-factor diagonal, $E \cos \theta = 93.5$.

3. Proceed along the vertical through this point to its intersection with the curve for the wire size used.

Read percentage of power loss per kilowatt per 1,000 ft. on the scale on the left.

Example.—Above data, No. 2 wire, 1.88 per cent.

4. Multiply this result by distance in thousands of feet, and load in kilowatts, and divide the square of the factor used in 1.

Example.—3,000 ft., 800 kw. — $P = \dfrac{1.88 \times 3 \times 800}{20^2} = 11.28$ per cent of 800 kw.

5. For two-phase or three-phase circuits the result is correct as it stands. For single-phase, multiply by 2 ($2 \times 11.28 = 22.56$ per cent).

6. On the B chart, locate the spacing between conductors on the scale at the lower right-hand corner of the chart. For unsymmetrical spacing use $\sqrt[3]{S_1S_2S_3}$.

7. Proceed vertically to curve for wire size used, scale on left gives value of X/R for 60 cycles. For 25 cycles multiply by 0.417.

Example.—Number 2 wire, 28-in. spacing; $X/R = 0.8$ for 60 cycles,
$X/R = 0.33$ for 25 cycles.

8. Proceed horizontally from X/R to the curve for the proper power factor and value of P. Read B on the scale at the bottom of the chart for curves to the right of the dividing line, on scale at the top for curves to the left.

Example.—Power factor 85 per cent, 60 cycle.

Interpolating between B for 80 per cent, power factor = 1.025 and B for 90 per cent power factor = 1.125 gives B for 85 per cent, power factor = 1.075.

9. Multiply B thus obtained by P as obtained in (4) and obtain V voltage drop in percentage of delivery voltage.

Example.— $P = 11.28$ per cent; $B = 1.075$;
$V = 11.28 \times 1.075 = 12.12$ per cent.

The delivered voltage was assumed to be 2,200 volts hence the voltage drop in volts is 12 12 per cent of 2,200 = 266.6 volts.

It will be seen that all the operations are simple and the computations such as can be readily made by slide rule. The summarized operation after finding P and B from the chart is simply:

$$V = \frac{1\ 88 \times 3 \times 800}{20^2} \times 1\ 075 = 12.12 \text{ per cent.}$$

Results in the above are referred to the voltage at the load. If it is desired to refer them to the voltage at the source end, the value of B as given is approximately correct for use with P figured in percentage of power at the source.

If greater accuracy is desired,

$$B_s = B_r \frac{100B_r + V_r}{100 + V_r},$$

where subscripts s and r refer to quantities referred to source and load respectively.

Charts Based on Approximate Method.—The approximate method is so useful in many cases that a series of charts are given which facilitates its use although they do not give a direct solution without computation.

Figure 144 gives resistance in ohms per 1,000 ft. for various wire sizes.

Figure 145 gives inductive reactance in ohms per 1,000 ft. for various standard wire sizes and various spacings at 60 cycles.

Figure 146 gives a graphical solution for $R \cos \theta$ and $X \sin \theta$. Take the proper value of R from Fig. 144, find intersection of circle corresponding to this value with proper power-factor diagonal; read $R \cos \theta$ on scale at bottom. Similarly for $X \sin \theta$, only using scale at left.

Figure 147 gives graphical solution for amperes per kilowatt, $I/kw.$, for any voltage and power factor. Reduce voltage to scale of chart by dividing by a convenient factor. Find intersection of voltage circle with proper power-factor diagonal; read $I/kw.$ on scale at left; divide by the factor used in reducing the voltage.

To solve a given problem, find $R \cos \theta$ and $X \sin \theta$ from Figs. 144, 145, and 146. Find $I/kw.$ from Fig. 147.

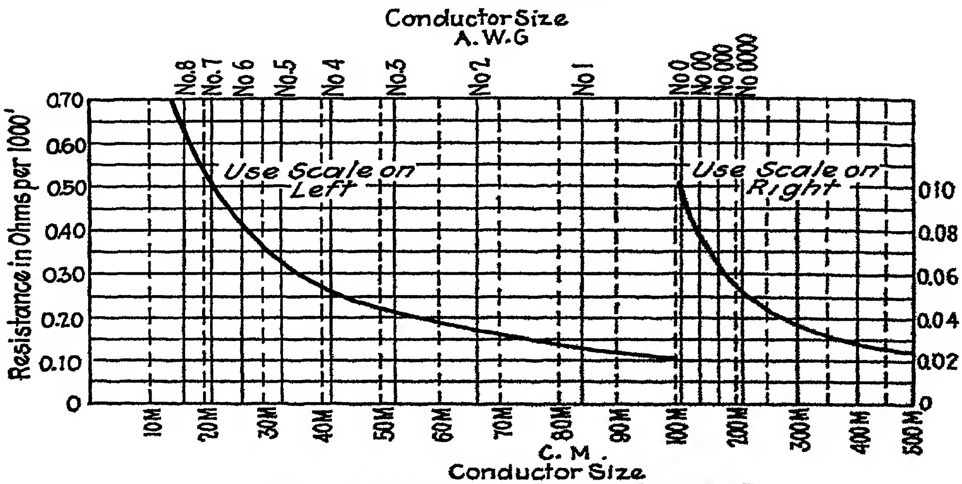


FIG. 144.—Resistance of copper conductors (R).

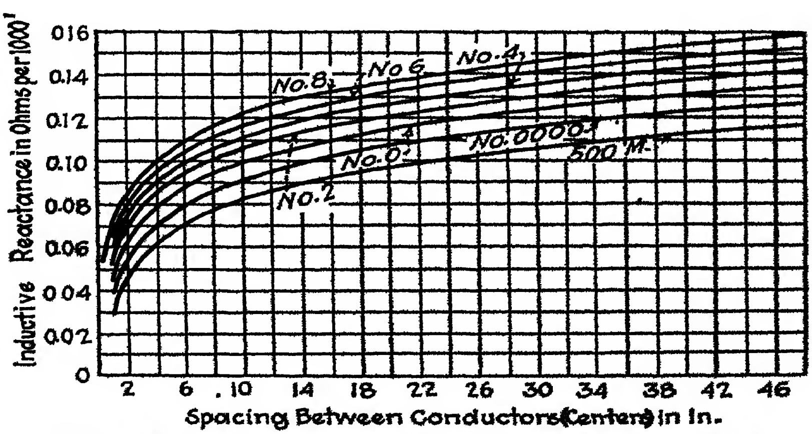


FIG. 145.—Inductive reactance of conductors—60 cycle (X).

$$\text{Volts drop} = (R \cos \theta + X \sin \theta) \frac{I}{kw.} \times kw. \times D.$$

D = length of line in thousands of feet.

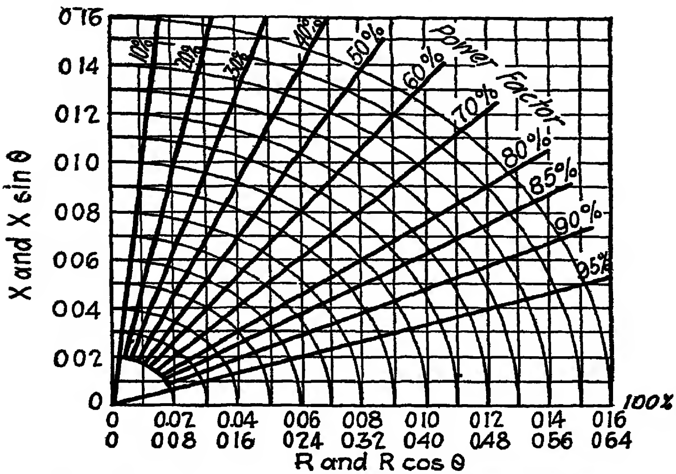


Fig. 146.—For computing $R \cos \theta$ and $X \sin \theta$.

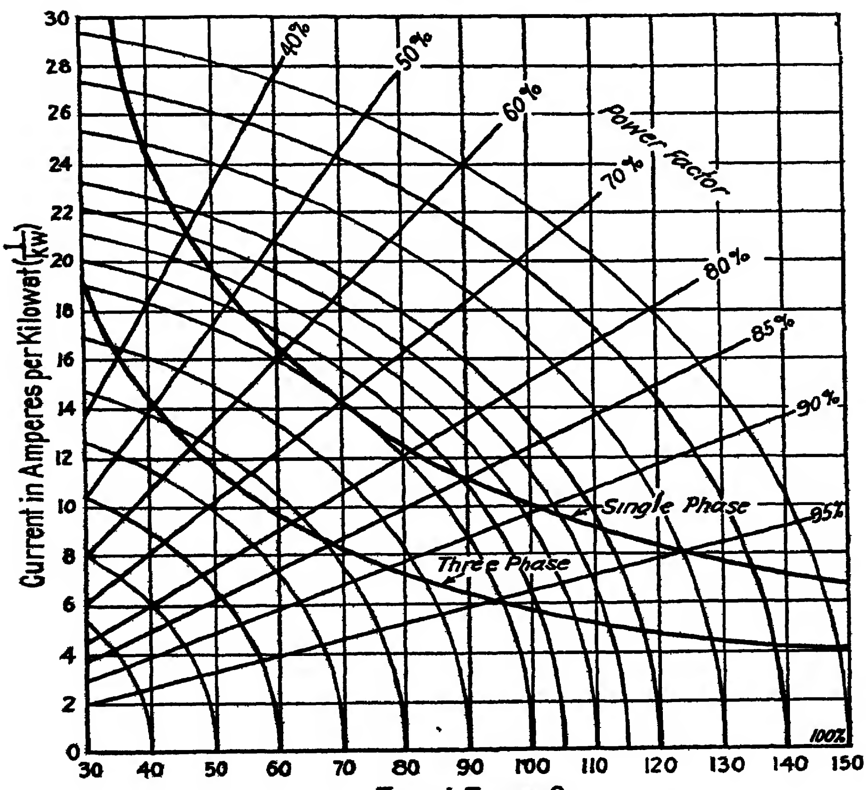


Fig. 147.—Current in amperes per kilowatt.

This is volts drop per wire.

For single-phase, multiply by 2 for total line drop.

For three-phase, multiply by $\sqrt{3}$ for volts drop between phases

Example.—500 kw, at 85 per cent power factor, three-phase, carried, 2,500 ft. with 2,200 volts (delivered). Wire size No. 2, spaced 20 in. (equivalent).

From Fig 144, R = 0 17 ohm per 1,000 ft.

Fig. 146, $R \cos \phi$ = 0.135.

Fig 145, X = 0 121

Fig. 146, $X \cos \phi$ = 0 073

$R \cos \phi + X \cos \phi$ 0 208

Fig. 147, using 2,200/20 = 110 volts.

$$\frac{I}{kw.} = \frac{6.5}{20} = 0.325 \text{ amp per kilowatt.}$$

Volts drop = 0 208 × 0.325 × 500 × 2 5 = 84.5 volts per phase 84.5 × $\sqrt{3}$ = 146 volts or 6.6 per cent.

CHAPTER XI

POWER LOSS

Whenever electrical energy is transmitted over a circuit having resistance, some of the energy is dissipated in heat generated by the passage of the current through that resistance. The amount of energy thus dissipated may be expressed by

$w = I^2R$ watts,

where

I = the current in amperes

R = the resistance of the circuit in ohms.

For single-phase circuits,

$w = 2I^2r,$

where

r = the resistance of one wire from source to receiver.

For three-phase circuits,

$w = 3I^2r$

where

r = the resistance of one wire from source to receiver

and

I = line current.

For two phase, three wire,

$w = 4I^2r$

where

r = the resistance of one wire from source to receiver, all wires being the same size

and

I = line current in outside wires (line current in third wire = $\sqrt{2}I$).

In Chap. X, "Voltage Drop and Regulation," the quantity power loss was used in connection with the computation of voltage drop by the chart method. Its derivation by formula was given with a chart for obtaining the per cent power loss on a distribution circuit. It is not necessary to repeat these here, but a brief discussion of the quantity and its application to the design of the distribution systems is in order.

Power loss is an important consideration for two reasons:

1. It represents a real loss of saleable product, hence is a distinct part of the cost of transmission and distribution of energy. Thus it plays a major part in the economical design of the system as shown more fully in Part III of this book.

2. Since the current from source to receiver (load) is practically constant for a distribution circuit, the loss in power must be evidenced by a drop in voltage. Therefore, as quality of service depends essentially on voltage regulation, the power loss and its accompanying voltage drop are of primary importance, as indicated in Chap. X.

Transformer Losses.—In addition to power losses in line conductors, the losses in transformers are also an important item. These are of two types:

1. *Core Loss,*—a constant 24-hr.-a-day loss as long as the transformer is excited, and independent of the amount of load carried.

2. *Copper Loss,*—a loss which varies with the load the same as the loss in the line.

These quantities are discussed in some detail in Chap. IX and examples of losses for a typical line of distribution transformers given.

Losses for Distributed Loading.—Where the load may be considered as uniformly distributed along the line, which is the case with many problems dealing with secondaries, the power loss may be computed as equivalent to the loss which would be occasioned by the total load, carried over one-third (1/3) the total length of the circuit. This may be proved mathematically as follows:

Referring to Fig. 148 which illustrates the distribution of the load, the total current at any point a distance x from the source end will equal

$$k_1(wl - wx),$$

where

w = load per unit length.
l = total length.
k_1 = proportionality factor to convert w to current.

The loss for any increment distance dx is therefore,

$$k_1^2(wl - wx)^2 r dx$$

r = resistance per unit length.

The total loss for any length x then equals,

$$\int_0^x k_1{}^2w^2r(l - x)^2dx$$
$$= k_1{}^2w^2r\left(l^2x - lx^2 + \frac{x^3}{3}\right).$$

For the total length, $x = l$, and

$$\text{total loss} = k_1{}^2w^2r\left(l^3 - l^3 + \frac{l^3}{3}\right) = \frac{k_1{}^2w^2l^3r}{3} = (k_1wl)^2\frac{l}{3}r$$

which is equal to the loss occasioned by the total load current k_1wl over one-third the total length l

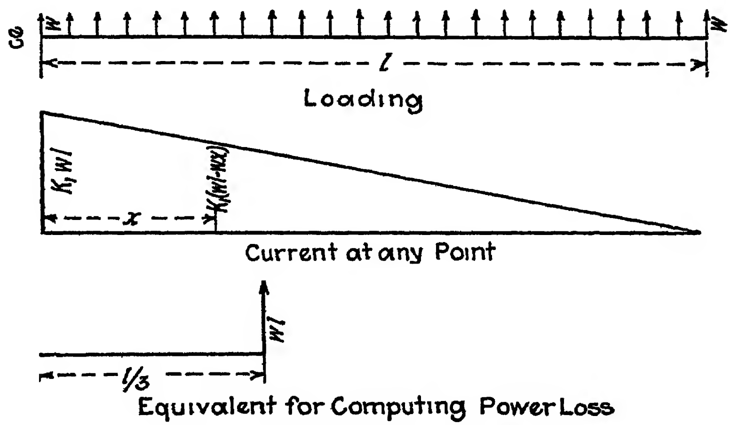


FIG 148.—Uniformly distributed load.

It should be noted that, if the computation for power loss is to be used as one step in the computation for voltage drop as was done in connection with the charts given in Chap. X, with distributed loading, the power loss must be computed as that for the total load over *one-half* the distance instead of one-third. This is on account of the fact that the voltage drop is computed as that for the total load at one-half the distance. Therefore, in making such computations, care must be taken not to use the power loss obtained for that purpose as the true power loss. The true power loss will be two-thirds as much.

Loss Factor and Equivalent Hours.—One very important point in regard to the computation of copper losses on line and transformers which, although fundamental, is quite often overlooked, is that they vary with the *square* of the current. In Chap. III the quantities, *loss factor* and *equivalent hours*, are dis-

cussed to some extent and their derivation indicated. Also, their relation to *load factor* is explained. While it is not necessary to repeat this again here, it is desired to emphasize the facts that *loss factor* is not equal to *load factor* except in a very special case. Its value lies usually somewhere between the value of *load factor* and (*load factor*)^2.

The use of *loss factor* and *equivalent hours* in determining total power loss are indicated below:

If $I_{\max}$ represents the current under peak-load conditions for the year (or any other period which is being considered),

R = the resistance of the circuit in ohms.

t = the *equivalent hours* per day for yearly peak to give a total loss equal to actual accrued loss = *loss factor* × 24.

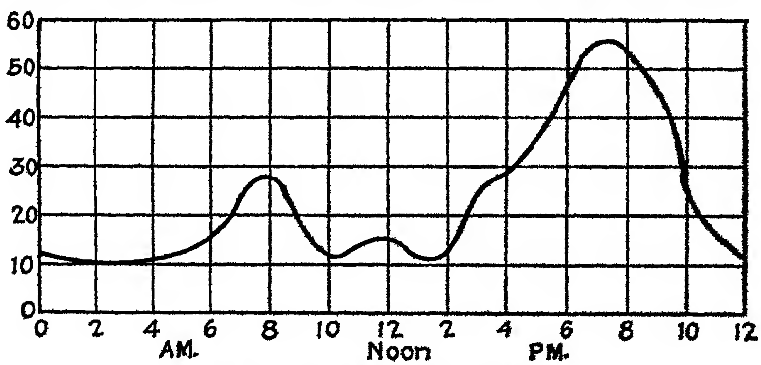


FIG. 149.—Typical daily load curve.

Then,

$I_{\max}{}^2R$ = the loss in watts at peak load.

$I_{\max}{}^2R \times t \times 360$ = the total loss in watt hours for the year.

If the average cost of losses per kilowatt-hour is known ($= C_e$), the yearly cost of losses will be equal to

$$Y_e = \frac{I_{\max}{}^2R \times t \times 360}{1{,}000} \times C_e \qquad (46)$$

An example of the derivation of the value for loss factor and equivalent hours is given below. As a rule this computation is rather difficult to make with exactitude for any class of load since the load varies considerably from day to day throughout the year as well as hourly during the day. It can be approximated, however.

Example.—Assume the daily load curve shown in Fig. 149 as a typical daily curve for the class of load to be studied. Taking the average load for

each hour during the day and squaring, the total loss for the day may be quite closely approximated ($\Sigma I^2 R$)

Hour	Average load-amperes	I^2
1	11	121
2	10	100
3	10	100
4	11	121
5	12	144
6	13	169
7	19	361
8	27	729
9	24	576
10	16	256
11	13	169
12	15	225
13	13	169
14	12	144
15	19	361
16	27	729
17	32	1,024
18	41	1,681
19	53	2,809
20	55	3,025
21	49	2,401
22	36	1,296
23	19	361
24	14	196
	Total I^2 =	17,267

This multiplied by the resistance of the circuit would give the watt-hours loss for the typical day.

Maximum current $- I_{max} = 55$ amp.

$$I_{max}^2 = 3{,}025,$$

$$\textit{Loss factor} \text{ for typical day} = \frac{\text{total } I^2}{I_{max}^2 \times 24} = \frac{17{,}267}{72{,}600} = 0.238.$$

Equivalent hours for typical day = *loss factor* $\times$ 24 = 5 73 hr.

The *loss factor* for the month may be somewhat different from that for the typical day due to the fact that although the day may be considered as typical or average for the month, the peak for the month may be higher than that assumed for the typical day. If it is 5 per cent higher, for example,

$$\textit{Loss factor} \text{ for month} = \frac{\text{loss factor for typical day}}{1.05^2} = 0\ 217.$$

Considering the period of a year, the *daily loss factor* will probably vary somewhat from month to month, more or less in inverse proportion to the number of daylight hours perhaps, if lighting load is being considered. Similarly, the peak load for the month will also vary as indicated by Fig. 150.

The *monthly loss factors* are assumed as shown in the table below. Each of these multiplied by the square of the ratio of the peak load for that month

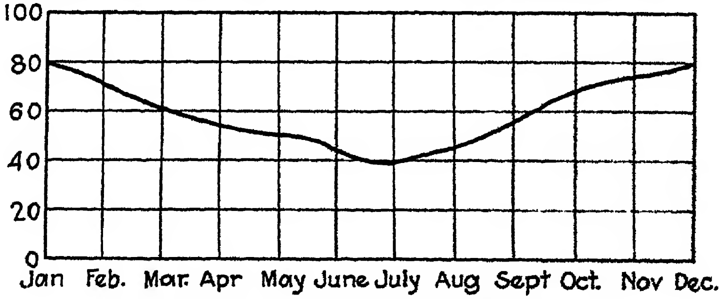


FIG 150.—Typical yearly load curve.

to the peak load for the year give the *loss factor* for the month in terms of *yearly peak.* The average of these for the twelve months gives the approximate *yearly loss factor.*

Month	1 Monthly loss factor	2 $\frac{\text{Monthly peak}}{\text{Yearly peak}}$	3 $\left(\frac{\text{Monthly peak}}{\text{Yearly peak}}\right)^2$	Columns 1 × 3
January......	0.280	1.00	1.00	0.280
February.....	0.260	0.88	0.78	0.203
March. . .	0.230	0.775	0.60	0.138
April...	0.215	0.67	0.45	0.097
May	0.200	0.625	0.39	0.078
June	0.180	0.55	0.30	0.054
July...... .. .	0.190	0.50	0.25	0.048
August.. .. .	0.200	0.57	0.325	0.065
September	0.217	0.70	0.49	0.106
October.......	0.230	0.85	0.72	0.166
November.... .	0.260	0.94	0.88	0.228
December......	0.280	1.00	1.00	0.280
Total... . ..	....	....	...	1.743
Average.. .	....	....	...	0.145

The yearly *equivalent hours* = 0.145 × 24 = 3.5 hours.

Relation of Losses to Efficiency.—It should be noted that high system efficiency, efficiency being defined as the ratio of power output to power input, does not necessarily represent the most desirable condition. Losses can always be reduced by increasing the conductivity, that is, by adding more copper. This, however, involves additional cost so that the benefit gained by the reduction in losses may be more than offset by

the increased cost of the conductors. An economic balance can be struck to determine how far losses can be economically reduced, due consideration being given to questions of probable increase in load, voltage, regulation, etc. This question of economic design is taken up in Part III so will not be dwelt on further here. It is sufficient to point out the essential fact that small losses do not necessarily indicate economy and that true economy can only be determined by taking into account all the factors of cost.

Sheath Loss.—Another form of power loss, which may be of considerable magnitude in some cases, is encountered when single-conductor, metallic-sheathed cables are used with alternating current. The load current in such a cable produces a magnetic field which induces voltage between the sheaths of the various conductors of the circuit. If the sheaths are connected together by being bonded or by each being grounded, this voltage will set up a circulating current along the sheaths. This represents a real power loss. In some cases it becomes of even greater importance than the resistance loss in the conductor itself. In any case it should be taken into consideration when single-conductor cables are used.

The magnitude of the sheath loss may be approximated

[1] . . . by assuming that there is an additional effective conductor resistance of such value that when this resistance is multiplied by the square of the actual current flowing through the conductor, the loss in the sheath will be obtained. The conductor resistance for a single-conductor cable in which induced sheath currents are allowed to flow is the following:

$$\text{Resistance} = R + R_0 = R + \frac{X_m^2 R_s}{X_m^2 + R_s^2} \text{ ohms per 1,000 ft.} \quad (47)$$

where R is the actual conductor resistance at a given temperature and frequency, and

$$X_m = 2\pi f\left(0.1404 \log_{10} \frac{2S}{r_5 + r_4} \times 10^{-3}\right) \text{ per 1,000 ft.}$$

$$R_s = \frac{1{,}503\rho_s}{r_5^2 - r_4^2} \times 10^{-6} \text{ ohms per 1,000 ft.}$$

ρ_s = resistivity of the lead sheath in microhm centimeter units which may be taken as 24.2 at 40°C., 25.2 at 50°C., 26.1 at 60°C.

S = distance between centers of conductors in inches.

r_4 = inner radius of lead sheath in inches.

r_5 = outer radius of lead sheath in inches.

f = frequency.

[1] SIMONS, DONALD M., "Calculation of the Electrical Problems of Transmission by Underground Cables," *Electric Journal*, August, 1925, p. 366

CHAPTER XII

FUSES AND OTHER DISCONNECTING DEVICES

Fuses.—Fuses are the most commonly used protective device on medium-and low-voltage circuits, *i.e.*, as protection against damage due to excessive currents. In general, they are efficient yet comparatively inexpensive and, when properly used, are in many cases a very valuable means for insuring apparatus against injury and circuits against complete interruption. The maintenance of a high degree of continuity of service on the ordinary type of distribution circuit is usually dependent to a large degree on the proper use of fuses at transformers, services, etc. However, for proper use, their characteristics and limitations must be understood.

Essentially, a fuse consists of a link of metal inserted into the circuit and of such material, size, and shape that it will carry the normal current in the circuit without overheating. If the current exceeds a certain amount, however, the fuse link will melt and hence break the circuit. Fuse links are usually made of lead, zinc, or similar metals, or alloys of such metals, or of copper of comparatively small cross-section.

The characteristics of the operation of a fuse depend upon the material used, its size, its shape, the holder or container in which it is mounted, and also on the nature of the circuit in which it is used, as to voltage, load, and system capacity. The properties of the fuse which should be chiefly noted are as follows. Most of these can only be determined accurately by actual test under the conditions under which the fuse is to be used:

a. Current Rating.—The current rating of a fuse should be approximately the current which it can carry continuously without blowing, but above which it will blow. This is likely to be a rather indefinite value, unless certain limiting conditions are specified, since not only will similar fuses blow at somewhat different values of current under similar conditions, but also external conditions, such as the radiation capacity of the holder, may have quite an effect on that value. The material of which the fuse is made is an important factor in accurate rating,

certain alloys showing much greater uniformity than other materials. At best, however, the fuse cannot, in most cases, be depended upon for certain operation within a narrow range of current values. Stock fuses or fuse materials are quite likely to be rated considerably above average blowing current, in fact, the National Electrical Code stipulates a rating of 25 per cent above actual test values of blowing current. Ratings should be determined for the particular conditions under which the fuse will be used regardless of its rating otherwise obtained.

b. Time Characteristic.—All fuses have the characteristic that the time in which they will blow, after the application of a current which will blow them, will be the shorter, the greater the value of that current. A typical time characteristic curve is shown in Fig 151. This characteristic varies with different fuses as is indicated by the curves *a* and *b*, some fuses having the time more nearly in simple inverse proportion to the current, while in others a very small amount of increase in current shortens the time very materially. Some fuses reach a very short blowing time (less than 1 cycle) within the range of practicable values, while others do not achieve anywhere near such short periods, even at the maximum values under which their use would be considered feasible. The time characteristic is dependent on the fuse material and also on the type of holder or container. In some cases the time is greatly accelerated by supplementary mechanical action.

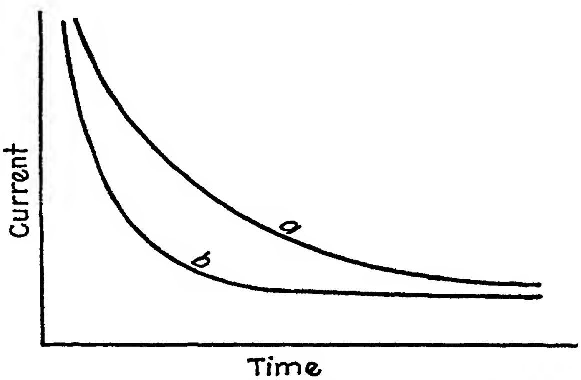


FIG. 151—Typical time-current characteristic for fuses.

c. Voltage Rating.—Fuses must be adapted to the voltage of the circuit on which they are to be used. This refers chiefly to the length of the fuse itself; it must be long enough to provide sufficient distance between contacts so that the arc formed by blowing will not carry across and continue the circuit. Also the mounting must have sufficient clearance and insulation from surrounding objects (case, box, etc), and from its support, to prevent arcs

to ground. In this regard it should be noted that, under normal operating conditions, the voltage between fuse contacts is very small but from either contact to ground the full line-to-ground voltage is found. After the fuse has blown, the full voltage to ground is likely to be imposed between contacts, and in some cases even full line-to-line voltage.

d. Ability to Clear the Fault.—The purpose in using fuses is, in most cases, so that they will interrupt the circuits in case short-circuit currents are passed through them. If they are not able to do this they are not only worthless but may be a real menace. A great many fuses sold under claims that they are suitable for certain voltages and certain short-circuit currents, fail miserably when put to actual test on a large system. On secondary voltages the problem of obtaining a satisfactory fuse is, in the majority of applications, not difficult. The energy interrupted is ordinarily not high comparatively and usually a simple type of fuse and holder is sufficient. For interior work, a cartridge or enclosed type is commonly used, while for outdoor line work a simple link held between contacts is customary, no special device for extinguishing the arc being necessary. On primary voltages, especially those of the order of 4,600 and above, the energy in the interrupted circuit may be considerable, depending on the short-circuit current obtainable and the voltage of the circuit. The intensity of the arc formed between the contacts by the blowing of the fuse depends to considerable degree on this energy. The ability of the circuit to maintain the flow of current across that arc depends somewhat on its length (distance between contacts) and also largely on the voltage which the system maintains across the gap. Both that voltage and also the short-circuit current are functions of the nature of the system behind the point of fault. For example, at a point near a large generating plant both these quantities will be much larger than at a distant point with several miles of intervening transmission and distribution circuits. It is this characteristic which causes some fuses to fail on a large system, especially near the power sources, when they may operate quite satisfactorily on a smaller system.

Several special means of extinguishing the arc are employed in different fuses—some such means being necessary for satisfactory operation at these higher voltages. The most important of these are:

1 Immersing the fuse element in a quenching liquid. Oil is used for this purpose in some cases, chiefly on fuses intended for underground manhole or vault use. One type of fuse uses a volatile liquid similar to carbon tetrachloride.

2 Enclosing the fuse in tube, tight at one end and open at the other. The force of the expulsion of the heated gases (caused by the blowing of the fuse) out of the tube tends to extinguish the arc.

3. Separating the contacts mechanically after the fuse blows by pulling them apart or interposing a barrier, thus drawing out or cutting off the arc. This is usually used in combination with 1 or 2.

4. Surrounding the fuse element with a deadening powder which tends to absorb the metallic vapor of the arc and extinguish it. Such a construction is quite similar to that used for the ordinary low-voltage cartridge fuse.

The size of the fuse used (*i.e.*, its rating) also has some effect on its ability to clear. A large fuse presents more gas to be disposed of on its blowing, which may be an advantage in an expulsion fuse but may be a difficulty in one in which the gas is absorbed. The time characteristic of the smaller fuse may also play a part. The author has seen tests in which a 15-amp. fuse of a certain type cleared a 10,000-amp. short circuit without distress, probably because it cleared in a fraction of a cycle before the current could rise to its full value, whereas a 50-amp. fuse of the same type failed to clear, blowing up. The shape of the fuse element and its material also probably have a considerable amount of influence on its ability to clear heavy short-circuit currents in that they affect the time characteristics and amount and rate of formation of the gas. At present no one of the types above mentioned can be recommended to the exclusion of the others. Satisfactory operation has been obtained with each under certain conditions. Some of the mechanical advantages and disadvantages will be cited later.

e. Ability to Clear Overloads.—A fuse must be able to clear satisfactorily currents only a little greater than its rating as well as heavy short circuits. Not all are able to do this. Certain fuses of the expulsion type are able to clear one or two such shots but in so doing the tube becomes carbonized and succeeding shots fail to clear, the energy of the expulsion not being enough to blow the arc clear. On heavy short circuits the energy of

expulsion is great enough to keep the tube clear. Fuses in which the gas is absorbed (1 and 4) are generally very satisfactory on overcurrent operation.

f. Mechanical Features.—There are several mechanical features of fuses and their holders which should not be overlooked in considering any particular design.

1. They should be safe to work with in inspecting and refusing. Usually the fuse is incorporated in a cutout by which the circuit may be opened when the fuse is removed. Exposed live contacts or other live parts increase the hazard. The design should be such that closing the fuse in on a short circuit will not endanger the operator unduly. This applies especially to expulsion fuses.

The cutout feature should be so designed that it may be operated under voltage without damage to the fuse or danger to the operator.

2. With fuses of the expulsion type and some others with supplementary vents, the blowing of the fuse is accompanied by a loud report, amounting even to a small explosion with the larger sizes and heavier currents. While this may not be dangerous and not a serious disadvantage in some locations, it is quite likely to be annoying, and perhaps prohibitively so, in enclosed places such as vaults or substation buildings.

3. Any fuse is likely to blow up on occasion if given a shot beyond its ultimate capacity. In such a case, a porcelain holder may become a menace due to flying particles of sharp, hard material. A box of fiber or even of wood will not present this hazard. The porcelain, on the other hand, has the advantage of being a good dielectric and, if of good quality, not as subject to deterioration as some other materials.

Use of Fuses.—Certain general principles should be observed in the use of fuses.

1. If the fuse is used to protect a piece of apparatus or a circuit against overload, its size should be carefully chosen so as to be well under the dangerous value of current but still as far as possible above the normal operating current, to prevent interruptions to the circuit on harmless temporary overcurrent conditions.

2. If the fuse is used to protect against short circuits only and not against overload, a larger size may be chosen, but care must be taken that it is not too large to clear promptly on the minimum short-circuit current which is probable.

3. Fuses are not as a rule adapted to selective operation, that is, in situations where it is desirable for one fuse to open and another one to remain closed, especially if the two are of anywhere near the same size. The most ordinary example of such a case would be two fuses in series. If one were twice as large as the other they might operate satisfactorily, but even so, if they had a very sharp time characteristic, a heavy current might cause both to open.

An exception to this might be where two fuses of different types were used, one with a sharp time characteristic and one with flat, see curves *a* and *b*, Fig. 151. In such a case the one with the sharp characteristic would probably open first in all cases if somewhat smaller than the other.

With Distribution Transformers.—One of the chief uses for fuses on the distribution system is in connection with distribu-

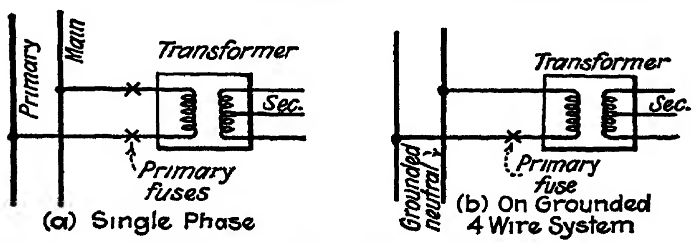


FIG 152.—Use of primary fuses.

tion transformers. It is quite generally the practice to insert fuses in the primary connections to such transformers, Fig. 152. Such fuses may be considered as protecting the transformer against overload or as being a means of clearing a short-circuited transformer off the primary mains and thus preventing a general interruption to service by the opening of the substation circuit breaker. The latter is usually considered the chief function of the primary fuse. Naturally, this purpose is also accomplished if the fusing is small enough for overload protection. In the latter case, however, short-time overloads are likely to blow the fuse, thus interrupting service unnecessarily when the transformer is in no danger of overheating. Since the power company's function is to give service, it seems logical to protect that service as far as it is reasonably possible in spite of possible occasional danger to equipment and to take some other means of protecting the equipment. In this case, frequent load checks offer a reasonable means of preventing undue overloads on transformers. In

choosing a primary fuse for any particular system or part of a system (or transformer perhaps) the characteristics mentioned above must be considered as follows:

Current Rating.—If fusing is intended to protect the transformer against *overload,* naturally a different size of fuse must be used with each size of transformer, their current ratings, in actual blowing current, being chosen so as to be below the value of current which is considered as an overload. For transformers operated continuously at full load for long periods of time, such as power-service transformers, the rated load may be considered the maximum allowable. The fuse size in this case should be equal to the full-load current on the transformer or possibly a little larger. On transformers serving lighting load, however, with a characteristically short-time peak load, especially in cold climates where the peak load is practically certain to come during cold weather, a load of 175 to 200 per cent of transformer rating may be necessary to damage the transformer materially. In this case, the fuse sizes may be based on some such value. For certain protection, however, this value should probably be low enough to protect the transformer against damage in hot weather, possibly at 150 per cent full-load rating, for example, although this would not allow the maximum possible safe load in cold weather. The sizes should be chosen as large as possible, and still give the desired protection, in order to prevent outages due to short-time overloads, non-uniformity of fuses, etc.

If the fusing is considered as chiefly for *clearing trouble* rather than for overload protection, the sizes may be somewhat larger than for overload protection. It is well to have the sizes large enough to avoid possible outages due to short-time or intermittent overloads which will not damage the transformer in any case, or to non-uniformity of fuses, or to emergency overloads which might be experienced, as in the case of banked transformers where the load of one transformer may have to be carried by others adjacent. On the other hand, the fuses must not be too large to clear troubles promptly. For transformers located a long distance from the generating source, the reactance of intervening lines may be sufficient to reduce the short-circuit current, even for a dead primary short, to a comparatively low value. The fuse must be small enough to clear on such currents, otherwise it is of little value, a short-circuited transformer

primary tripping the station circuit breaker rather than blowing the fuse. From this consideration only it might seem that the same size of fuse for all sizes of transformer would be satisfactory provided it were smaller than the minimum primary short-circuit current. This is true to a certain extent. However, short circuits on the secondary windings or turn-to-turn shorts in the primary may give considerably less than full primary short-circuit current and yet it is desirable to clear these as promptly as possible. Hence, it is advisable, ordinarily, to grade the fuse sizes according to transformer size, establishing some minimum value such as 200 or 300 per cent of full load as a basis, which will care for the first point mentioned above. Naturally, for locations near large generating sources, especially on underground systems, the short-circuit current is likely to be relatively high and the grading of fuse sizes becomes relatively less important.

Time Characteristic.—The time characteristic may become important in the primary fuse if it is used in connection with other fuses. For example, with a transformer feeding a single service there will be large secondary fuses on that service on the customer's board. The time characteristic of the primary fuse should be such that it will not blow before the secondary fuses do, in case of a heavy short on the service wiring.

Voltage rating, ability to clear faults and overloads, and mechanical features should all be studied, by actual test if need be, to make sure that the fuse will fulfill its duty under all circumstances of normal operation or emergency.

Secondary Fuses (Not Including Customers' Fuses on Individual Services).—Secondary fuses are usually used with distribution transformers on overhead secondaries only when the transformers are banked together on a common secondary. There are two different ways in which this is done, as was explained in Chap. VII under "Secondary Banks."

In some cases *sectionalizing fuses* are installed in the secondary midway between the transformers, Fig. 153. These fuses are comparatively small since normally they would not carry much current—only the unavoidable interchange one way or the other as the load varies or on account of it being impossible to locate them at an exact neutral point. If one transformer should go out, however, its load will be fed by adjacent transformers through the fuses and if the current thus passing is of any considerable amount, it will blow these fuses thus interrupting service

to the section of secondary fed normally by the damaged transformer.

The other practice is to fuse the secondary connections *to each transformer*, Fig. 154. In this case the fuse is expected to blow in case of a short in the transformer thus clearing it from the *secondary bank*. Shorts on the overhead secondary mains themselves are comparatively unusual and will ordinarily burn clear

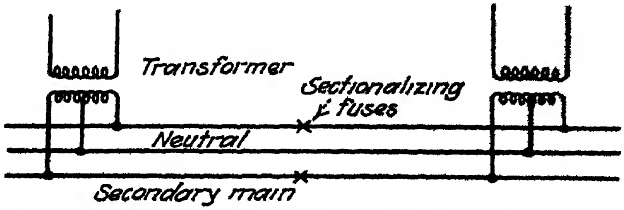


Fig. 153.—Use of secondary sectionalizing fuses.

without blowing transformer fuses. This practice allows full advantage to be taken of the banking of transformers. Reserve capacity must be retained in each transformer, however, to take care of emergency overloads due to adjacent transformer outages. The size of the fuse also requires careful consideration. In general, the factors affecting the size of the primary fuse as discussed above will also apply here and it is well to have the second-

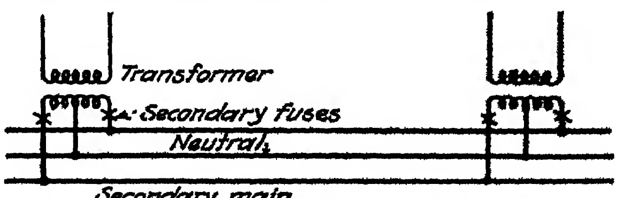


Fig. 154.—Use of secondary fuses at each transformer.

ary and primary fuses for any transformer correspond in size. One further point is important. Since the fuse is expected to blow on a short circuit in the transformer, its size must be such that the short-circuit current which can be developed at that point (depending on the distance from other transformers, size of secondary wires, sizes of other transformers, etc.) will cause it to blow. This factor may have an important bearing on the design of the bank as to transformer size and arrangement.

Fuses in grounded neutrals either primary or secondary are unnecessary and are usually omitted. In case of the sectionaliz-

ing secondary fuses their presence might create a danger in possibly breaking or at least reducing the effectiveness of the ground on the neutral

Secondary Fuses in Underground Alternating-current Secondaries.—On some of the most recent underground alternating-current secondary networks installed, fuses are entirely omitted from both mains and service branches, faults being expected to burn clear. In order to have some assurance that this will happen, the network must be carefully designed as to size of cables and connected transformer capacity. Otherwise, fuses should be used for disconnecting faulty branches or sectionalizing trouble. In doing so, care must be taken not to get fuses of too nearly the same size in series on any fault current, otherwise unwishedfor openings will occur and the trouble will not be localized.

Fuses in Underground Direct-current System.—Fuses are quite generally used on direct-current mains, branches, and ser-

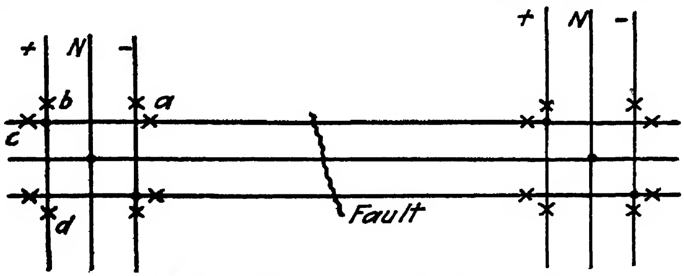


FIG. 155 —Fuses on direct-current network.

vices at all junction points, also on feeders, at the network end, except on the very largest sizes where circuit breakers are sometimes employed. In this case, the network connections furnish multiple paths for fault current into the faulty section of cable, assuring the blowing of fuses only at the ends of the faulty section even though they are of the same size as other fuses on the system, since the current through them is considerably larger than through the other fuses, Fig. 155. The current through fuse *a*, for example, is the sum of those through *b*, *c*, and *d*.

Primary Fuses on Branch Lines.—Primary fuses are sometimes used on branch lines, such as long branches off main circuits in rural districts. Their purpose is to clear short circuits occurring on these branches without interrupting service on the main circuits, also to act as convenient disconnects to help in locating

faults. The danger here is that these fuses as well as the transformer fuses may blow in case of trouble in a transformer, thus interrupting all the service on the branch line and making the trouble harder to find. The importance of maintaining continuous service on the main circuit may outweigh these objections and point to the use of fuses, but otherwise they are likely to be a source of trouble unless the time characteristics and sizes are very carefully proportioned in relation to those of the transformer fuses. For disconnecting purposes only, other satisfactory means may be found.

Fusing Underground Services off Overhead Lines.—Troubles on underground services off overhead lines either at primary or secondary voltage, while not more likely to occur than on the overhead part of line, are more difficult to locate when they do occur. Hence it is advisable, if possible, to install fuses on such services at the cable pole. The general precaution of not having fuses of similar size and characteristics in series must be observed here, however, since such additional fuses, either on the lines outside or the service inside, may defeat the purpose of the fuses in question.

Other Disconnecting Devices.—There are several other disconnecting devices in common use on distribution systems, some of the most important of which will be taken up and discussed briefly.

Oil Circuit Breakers.—Oil circuit breakers are generally used on the substation ends of primary feeders for the purpose of opening and closing the circuit when desired, whether or not under load, also for automatically opening the circuit when subjected to short-circuit currents due to faults on the circuit. An oil circuit breaker is essentially a switch whose contacts open under oil which quenches any arc which may tend to form on the opening. For the above purpose they must be so designed as to interrupt the maximum short-circuit current which may be imposed on them.

Similarly, oil circuit breakers must be used at points on the system, elsewhere than at substations, where a like duty is imposed, *i.e.*, the necessity for interrupting heavy short-circuit currents. Such locations are, for example, at large customers, fed at primary voltage, used as a master switch controlling the whole service (and sometimes also on branch circuits) when the short-circuit duty is greater than can be handled by fuses, or on loop power lines to sectionalize the loop, etc.

Oil switches suitable for switching load current but not designed for interrupting short-circuit current are sometimes used on primary branches, services, etc., where the load current must be interrupted comparatively frequently and where it is not necessary to clear fault currents. These are always used in series with some other device, oil circuit breaker, or fuse which can interrupt short-circuit current. An example of this is the double-throw switch mentioned in Chap. VI, by which a primary service can be thrown from one to the other of two separate feeds, either automatically or manually. A fuse is used in series, either in each of the feeds or in the service branch from the switch, to clear the circuit in case of a fault.

The use of oil circuit breakers or switches is very largely confined to substation, vault, or manhole installations, since such apparatus is somewhat difficult to install and maintain on poles for ærial circuits and there is, as a rule, less necessity for opening ærial lines under load. Some limited applications are found, however.

The oil switch is probably the most dependable and convenient to operate of any of the disconnecting apparatus available, but it is likewise the most costly, hence its use is generally limited to those applications where other apparatus is not satisfactory.

Air-break Switches.—Air-break switches are generally used (at primary voltages) in locations where it is necessary to open the circuit under voltage only, with no load current or at least a very small amount. The current they must interrupt is hence only the charging or exciting current of lines or apparatus connected. Under certain conditions, however, this current may be of sufficient amount to make an oil switch advisable.

Air-break switches are sometimes used in the form of a gang-operated pole-top switch. These generally are equipped with auxiliary horn gaps to take care of the arc and are capable of breaking a certain amount of load current. See Fig. 323.

Another common form is the ordinary disconnecting switch which is usually operated one pole at a time. They are generally not designed to break any great amount of current and their use should be limited to points where no load current and only a small charging current must be interrupted.

Air-break switches are used at jumpering points between overhead lines, on cable poles to disconnect the overhead from the cable, at branch points to disconnect branch lines, and to dis-

connect apparatus such as oil circuit breakers or transformers (where the load current may be otherwise broken), etc.

Air-break switches at secondary voltage are quite commonly used to interrupt load currents where fuses are not suitable on account of the size of the current or the necessity for reclosing the circuit promptly. The chief use for such switches on the distribution system is on direct-current feeders, the station end of which are quite generally equipped with air-break switches. On some of the larger feeders (of the order of 2,000,000 cir. mils) remotely controlled manhole circuit breakers have been used in some cases for switching at the network end of the feeder. Another use which has come into prominence recently is the automatic network protector or unit used in connection with alternating-current secondary networks. They have been described quite fully in Chap. VII and it need not be repeated here.

Disconnecting potheads are essentially single-pole, air-break switches with the contacts enclosed, or nearly so, in porcelain, at least when the circuit is closed. They find convenient use at jumpering points, primary branches, etc., where little charging current need be broken. See Fig. 322.

Fused Cutouts.—A majority of holders for primary fuses are designed so that either the fuse acts as a cutout or there is a separate cutout or switch in connection. They are in this regard essentially an air-break switch or disconnect, generally used in connection with distribution transformers, etc.

Various types of *lugs, clamps*, etc., are also sometimes used as disconnects, being in purpose and action essentially air-break switches.

CHAPTER XIII

LIGHTNING ARRESTERS

One of the chief sources of trouble on overhead distribution circuits is lightning. It results in damage to wires, insulators, poles, and other equipment and apparatus, especially transformer windings.

A brief description of the generally accepted theory of the nature of lightning disturbances might not be amiss. A storm cloud is conceived of as having a heavy static charge of either + or − polarity. Hence it induces a charge of equal strength but opposite polarity in the earth beneath it, see Fig. 156. Where an electrical line occurs beneath the cloud, it finds itself

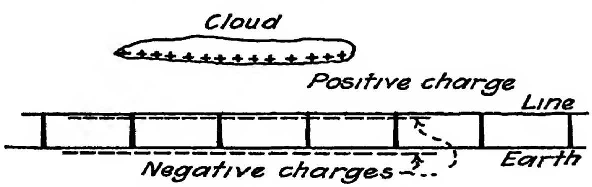


FIG. 156.—Charges due to storm cloud.

in this electrical field and, being connected to the earth through the conductance of its supports (even though such conductance is relatively small), it will also be negatively charged. If a discharge takes place between the cloud and the earth, the line may be effected in one of two ways. The discharge or lightning stroke may hit the line or its supports directly. There is an enormous amount of energy dissipated in a short period of time. The stroke seeks the ground by the shortest path and usually damages that path considerably in its course. Such an occurrence results in shattered poles, broken insulators, burned wires, etc. It is usually considered impracticable if not impossible to protect distribution lines against all such strokes.

The other effect is one induced in the line when the discharge takes place at some other point than on the line itself. In this case, the charges on cloud and earth neutralize each other by the

stroke, but the charge in the line, due to the fact that the line is insulated from the ground, cannot discharge so rapidly The result is a surge traveling along the line in both directions, seeking an outlet to earth, until its energy is expended by corona, leakage, and losses in the conductor, unless otherwise discharged. The voltage of the original surge in any case is proportional to the height of the line above ground.

It is probable that the height of such induced surges is considerably limited on distribution circuits as compared with higher voltage transmission circuits not only by the fact that they are, in general, actually closer to the ground, but also by their proximity to trees along the line, the presence of secondaries with grounded neutral, etc. Also, the comparatively low insulation to ground allows the surge to dissipate much more rapidly and hence not to travel any great distance. It is impossible to say at this time what values the surge will reach nor how far it will travel before being reduced to an insignificant value but it seems probable that, on the ordinary distribution circuit, this distance will not be over a half mile or so from the point of origin.

Such a surge entering the windings of a transformer will seek out any weak point in the insulation to ground and puncture through. This effect is magnified by the fact that the transformer winding presents a highly inductive path which has the effect of building up the voltage at the terminals. End turns of transformer coils are more highly insulated to provide against this effect.

The best protection we have against such a surge is the lightning arrester installed as close as possible to the apparatus which it is to protect. Its effect, if it performs properly, is to allow the energy of the surge to escape to ground through it without allowing the normal energy on the line to follow it and continue the arc, forming a ground on the line.

A lightning arrester consists essentially of two features:

1. An air gap, or series of gaps, so proportioned that it will not flash over at normal line voltage or at a voltage high enough above line voltage to insure against unnecessary, undesired operation, but will flash over under voltages of the order of lightning surges which might damage the apparatus which the arrester protects.

2. Some method for extinguishing the arc formed by this flashover and preventing the power arc from following.

Several different methods are used in different arresters for accomplishing this purpose. The simple horn gap makes use of the fact that the arc will rise and thus pull itself out as the horns separate. This type does not operate as fast as some other types, however, and the discharge is likely to be accompanied by other secondary surges induced in the circuit. In this and some other types, the gaps are in series with resistances which oppose the power arc. In others, the material of the conducting path through the arrester is such that it allows the surge to pass but offers a high resistance to the power arc.

The characteristics of the arrester which should be considered in choosing the proper type are:

1. *Speed of Discharge.*—It must be fast enough to relieve the stress on the apparatus promptly.

2. *Voltage Retained on Line.*—In some arresters the resistance to discharge increases with the amount of current, in others it decreases, the completeness with which the surge is discharged in a given time being affected accordingly.

3. *Voltage Setting.*—The voltage above which the arrester will discharge should not be so low as to cause discharge on unimportant surges but should be low enough to insure prompt action with dangerous values of voltage. Two to two and one-fourth times normal line voltage to ground is a common figure.

4. *Thermal Capacity.*—Some arresters will stand more repeated discharges than others without damage to themselves. Such discharges may occur with arcing grounds on an ungrounded system, for example.

5. *Action of Arrester on Failure to Operate.*—Some arresters, if damaged so that they will not operate to clear the power arc, hold on as a direct path to ground without visible evidence of failure. Such trouble is difficult to locate. An arrester which will blow up on such failure has the advantage in this regard, especially on an ungrounded circuit where an arcing ground at some point may induce failure in an arrester which, if not cleared, produces a double ground on the line.

Grounding.—No arrester can be effective unless it is properly grounded. There will be no positive indication of this until the protected apparatus is damaged. The arrester simply does not function and hence is of no use. This indicates the desirability of careful attention to the securing of a good, low-resistance ground. A water-pipe connection is of course the most desirable,

but since the path from arrester to ground should be as short and straight as possible, this type of connection is often difficult to make at a line-transformer location. If a driven rod is used, it should be long enough to reach permanent moisture if possible, if not, two or more rods as far apart as practicable will decrease the resistance. Salting the rod with sodium chloride or copper sulphate, and other means are sometimes employed to reduce the resistance of the ground. No such means is generally recognized as desirable, the corrosive action of the chemical in some cases materially shortening the life of the ground rod. In other cases the effect is only temporary. Since probably the greater part of the resistance of the ground connection as a whole is in the earth itself around the rod (for a radius of several feet), and the contact resistance between rod and earth is only a part of the total, it seems logical to assume that more stress should be laid in having rods long enough to reach moist soil and having enough rods (at fairly wide spacing), than on the diameter of the rod or the condition of the soil immediately around it.

Use of Arresters.—Investigation carried on in several places have indicated quite clearly the advantages of using lightning arresters at every transformer location as a means of preventing burning out of transformers. Regular spacing of arresters at intervals of ½ mile or so is sometimes practiced but is no doubt not as effective on account of the comparatively short distance which the surge probably travels and the likelihood of a surge originating between arresters and near a transformer.

The use of an arrester at each transformer, regardless of how small the transformer, is subject to some economic consideration, of course. If the arrester cost is high in comparison with the cost of the transformer itself and in comparison with the number of burnouts probable, it may be economical to omit them. Consideration must also be given to the value or necessity of maintaining service, however. On important service the arrester is good insurance.

As a rule, lightning arresters should also be installed on all cable poles, where the circuit passes from overhead to underground or *vice versa*.

Location of Arrester.—A good general rule for locating the arrester is to place it as close as convenient to the apparatus to be protected. This may be somewhat modified by considerations of practicability of construction, and also, in some cases, by the

advisability of placing the arrester where the height of the surge voltage may be most severe, in order to accelerate its operation.

General Considerations.—A few general points regarding the behavior of lightning and lightning arresters should be borne in mind in studying this problem:

1. That a lightning surge travels with practically the speed of light and hence a few feet of circuit more or less should make little difference comparatively in the protective value of an arrester.

2. That the surge has a very steep front as a rule but the steepness of the front and the height of the surge are changed by every change in characteristics of the circuit to ground (as to surge impedance, which is denoted by $\sqrt{L/C}$). At such points of change a partial reflection usually takes place with sometimes an attendant piling up of the voltage.

3. That a lightning arrester will not necessarily prevent a surge from striking or entering the apparatus protected, in fact in most cases it will have no such effect. Its function is rather to discharge quickly enough after the surge voltage is applied to prevent that voltage from having time to damage the insulation of the apparatus protected.

4. That the effectiveness of an arrester, aside from its own internal characteristics, depends on the ability of the ground connection to discharge the abnormal current to the ground. This makes it a requisite that the whole connection from arrester to ground, including wiring, ground rod, and ground itself must be of as low impedance as practicable.

CHAPTER XIV

FUNDAMENTAL THEORY

It is intended in this chapter to review briefly some of the more important fundamentals of electrical theory which underlie the work given in the preceding chapters. It will serve as a ready reference on such points.

Voltage and Current.—Voltage is the term applied to difference in electric potential which exists between two points such as the terminals of an electric circuit. The unit of voltage is the *volt*.

When voltage is applied across the terminals of a closed electrical circuit it causes an electrical *current* to flow through that circuit. The unit of current is the *ampere*.

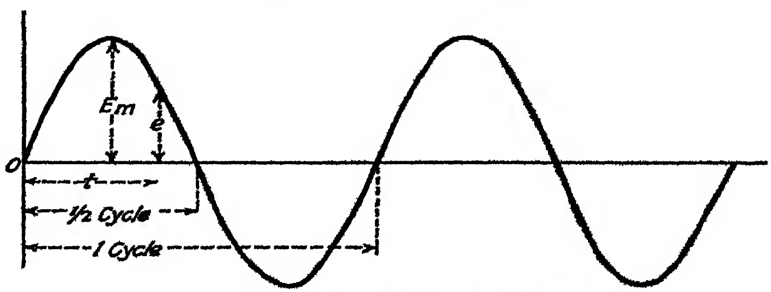


FIG. 157.—Sine wave voltage diagram.

If the voltage and current are in one direction only through the circuit, the circuit is termed a "direct-current" circuit. The voltage may be of constant magnitude, such as that produced by a battery, or it may be pulsating, such as that coming from a rectifier, that is, rising from 0 to a maximum then falling to 0 again in periodic cycles but without reversal. The usual direct current for general distribution produced by a rotating machine (generator or converter), is, in effect, of constant magnitude or continuous.

In an *alternating-current* circuit the voltage and current pass through periodic cycles of reversal, the number of complete cycles in 1 sec. being termed the "frequency." The ordinary

alternating current for general commercial distribution is usually intended to follow approximately a sine wave, *i.e.*, its instantaneous values through each complete cycle follow, proportionally, the values of sine θ as it passes through a complete cycle from $\theta = 0$ to $\theta = 360°$. This is illustrated by Fig. 157. The relations between instantaneous and maximum values are expressed by the equations:

$$e = E_m \sin \omega t = E_m \sin (2\pi ft) \tag{48}$$

$$i = I_m \sin \omega t = I_m \sin (2\pi ft) \tag{49}$$

where e and i are instantaneous values of voltage and current at any time t

E_m and I_m are maximum values of voltage and current.

ω = frequency expressed in angular measurement, radians per second.

$\omega t = 2\pi ft$ radians.

(2π radians = 360°.)

f = frequency in cycles per second.

t = elapsed time in seconds.

The values for voltage and current ordinarily used, *i.e.*, those which are measured by the ordinary voltmeter and ammeter are the integrated averages for a half cycle rather than maximum values. They are called "effective voltage" and "effective current."

$$\text{Effective voltage, } E = \frac{E_m}{\sqrt{2}}.$$

$$\text{Effective current, } I = \frac{I_m}{\sqrt{2}}.$$

Resistance.—Resistance is a property of an electrical circuit which opposes the passage of a current through it. It is a property of the material itself of the conductor rather than the arrangement of conductors and is effective against both alternating and direct currents. It is akin to "electrical friction" and results in a loss of power in direct proportion to the value of the resistance. Resistance is expressed in *ohms*.

For a conductor of uniform cross-section such as a wire, the resistance may be obtained from

$$R = \frac{\rho L}{A} \tag{50}$$

where

R = the total resistance.
L = the length.
A = the cross-sectional area of the conductor.
ρ = the *resistivity*.

Resistivity is expressed in various terms but probably the most convenient for the present purpose is that of *ohms per mil foot*, L being given in feet and A in circular mils.

Resistivity of a metal varies somewhat with its temperature but the effect is comparatively small and may usually be disregarded in the problems concerning distribution circuits. *Skin effect* also has an influence on resistivity when dealing with alternating currents. With copper wire this is also usually negligible. With steel and copper-covered steel conductors the skin effect may be appreciable, especially in the larger sizes. For copper-covered steel, the increase in resistivity is from 5 per cent in the smaller sizes, to 25 per cent in sizes about No. 0000, and as much as 80 to 100 per cent in large stranded cables. For steel wires the effect depends on the composition and hardness (which also affect the resistivity with direct current). With harder steel the increase with alternating current is negligible but with softer steel it may run from 50 to 100 per cent. Steel also has the characteristic that resistance to alternating current increases with the current to a certain value, then decreases for higher values.

Table VIII gives approximate values of resistivity of the various ordinary conductor materials:

Tables IX and X give values of resistance per 1,000 ft. for various standard sizes of wires.

TABLE VIII.—RESISTIVITY OF CONDUCTOR MATERIALS (DIRECT-CURRENT) AT 20°C. = 68°F.

	Ohms per Mil Foot
Copper—100 per cent pure	10 371
Copper—commercial	10.6 to 10.8
Aluminum	17
Aluminum—steel reinforced (6/1)	17.3
Steel—soft (EBB)[1]	50 to 60
Steel—hard (high strength strand)	100 to 120
Copper-covered steel[1]—30 per cent	35
Copper-covered steel[1]—40 per cent	26.3

[1] Skin effect appreciable for alternating current (see text).

TABLE IX —RESISTANCE OF WIRES AT 20°C. (68°F.) IN OHMS PER 1,000 FT.

Gauge, B & S	Area, circular mils	Copper, 100 per cent, solid	Copper 97 per cent		Aluminum		Aluminum, steel cored	Copper-covered steel 30 per cent		Copper-covered steel 40 per cent	
			Solid	Stranded[1]	Solid	Stranded[1]		Solid	Stranded[1]	Solid	Stranded[1]
No 8	16,500	0 6282	0 649	0 662	1 03	1 05	1 045	2 13		1 60	
7	20,800	0 4982	0.515	0 525	0 817	0 834	0 8293	1 69		1 27	
6	26,300	0 3951	0.407	0.416	0 648	0 661	0 6577	1 34		1 01	
5	33,100	0 3133	0 323	0 330	0 514	0 524	0 5217	1 06		0 799	
4	41,700	0 2485	0 257	0 262	0 408	0 415	0 4150	0 844		0 633	
3	52,600	0.1970	0.204	0 208	0 323	0 329	0 3291	0 670		0 503	
2	66,400	0 1563	0 161	0.165	0 256	0 261	0 2610	0 531	..	0 398	
1	83,700	0 1239	0 128	0 131	0 203	0 207	0 2070	0 421		0 316	
0	106,000	0.0983	0.101	0 103	0 161	0 164	0 1639	0 331	0 344	0 248	0 258
00	133,000	0 0779	0 0805	0 0821	0 128	0 1294	0 1294	0 262	0 272	0 197	0 205
000	168,000	0 0618	0.0638	0 0650	0 101	0 1026	0 1026	0 208	0 216	0 156	0 162
0000	212,000	0 0490	0 0505	0.0515	0 0804	0 0816	0 0816	0 165	0 172	0 124	0 129
	250,000			0 0437							
	300,000			0 0364		0 0578					
	350,000			0 0312							
	400,000			0 0273							
	450,000			0 0243							
	500,000			0 0219		0 0347	0 0347				
	750,000			0 0146		0 0230					
	1,000,000			0 0109							

[1] 2 per cent added to resistance of solid wire to obtain that of stranded

TABLE X.—RESISTANCE TO DIRECT CURRENT AND EFFECTIVE RESISTANCE TO ALTERNATING CURRENT OF SAMPLES OF VARIOUS GRADES OF DOUBLE-GALVANIZED STEEL CONDUCTOR

(Data from Indiana Steel and Wire Company)

Size	Material	Direct-current[1]	Effective resistance in ohms per 1,000 ft.									
			60 Cycles					25 Cycles				
			5 amp.	10 amp.	15 amp	20 amp	25 amp	5 amp	10 amp	15 amp	20 amp	25 amp
3/8 in.	High-strength strand....	1.106	1.112	1.116	1.124	1.132	1.142	1.105	1.106	1.110	1.124	1.135
3/8 in.	Siemens-Martin strand	1.022	1.031	1.035	1.040	1.051	1.065	1.027	1.029	1.036	1.044	1.054
3/8 in.	Standard strand..	0.686	0.741	0.771	0.827	0.943	1.067	0.707	0.728	0.771	0.830	0.875
1/2 in.	Siemens-Martin	0.637	0.644	0.648	0.649	0.652	0.658	0.639	0.640	0.642	0.644	0.646
1/4 in.	Siemens-Martin	2.315	2.32	2.345	2.375	2.415	2.47	2.31	2.33	2.37	2.41	2.465
No. 8 BWG	Three-ply, twisted guy wire	1.026	1.086	1.134	1.217	1.343	1.435	1.044	1.063	1.115	1.205	1.270
No. 6 BWG	BB telephone wire....	1.67	2.54	3.26	3.375	3.325	3.22	2.14	2.55	2.57	2.515	2.495

[1] At 5 amp. This increases somewhat with current on account of temperature rise

TABLE X.—(*Continued*)
RESISTANCE OF GALVANIZED IRON (STEEL WIRES) AT 20°C. (68°F) IN OHMS PER 1,000 FT, FOR DIRECT CURRENT
(Solid Wire)

Gauge, B W G	Area, circular mils	Resistance in ohms per 1,000 ft.		
		Steel	B.B.	E B B.
8	27,200	3 28	2 81	2 35
7	32,400	2.76	2 37	1 985
6	41,200	2 17	1.862	1 557
5	48,400	1.845	1 585	1 327
4	56,600	1 575	1 353	1 132
3	64,500	1.333	1 145	0 957
2	80,700	1 108	0 950	0 795
1	90,000	0 990	0 852	0 712
0	115,690	0 772	0 663	0 555

Inductance.—Inductance is a property of an electrical circuit which opposes any change in the magnitude of the current passing through it. It thus is effective against alternating current which is constantly increasing or decreasing but not against direct current of constant value. It is due to the interlinkage of the conductors with the magnetic flux caused by the current in the circuit. The unit of inductance is the *henry* or *millihenry* $\left(\frac{\text{henry}}{1{,}000}\right)$.

Inductance effects on a distribution circuit are of three types:

1. Effect in a conductor due to the current in that conductor.
2. Effect in a conductor due to the current in the return conductor of the same circuit.
3. Effect in the conductor of one circuit due to the current in other adjacent circuits.

The third effect is generally considered negligible although there is no doubt that in certain cases it may be appreciable.

The first and second inductance effects are expressed by the equation,

$$L = 0.1408\left(\log_{10}\frac{b}{a}\right) + 0.0152\mu$$

millihenrys per conductor per 1,000 ft. (51)

where

a = radius of conductor in inches.

b = distance between centers of conductors in inches.

μ = permeability of material.

For copper or aluminum $\mu = 1$.

For copper-covered steel—small sizes $\mu = 8$.

For copper-covered steel No. 0000 $\mu = 4$.

For copper-covered steel stranded $\mu = 6$ to 26 according to stranding and size.

For steel μ varies with composition, size, current, and frequency approximately as follows:

High strength............	13 to 16 (increases with current).
Siemens-Martin..........	13 to 18.
Standard strand	30 to 60 (60 cycles).
Standard strand........ ..	40 to 80 (25 cycles).
B.B.	235 to 260 (60 cycles).
B.B.........	300 to 425 (25 cycles).

The above formula is used for both single-phase and three-phase. For unsymmetrical spacing on three-phase, $b = \sqrt[3]{b_1 \times b_2 \times b_3}$.

The opposition of a given amount of inductance to the passage of a current is called *inductive reactance.* This is a quantity dependent on the rate of change of the current. It is expressed in ohms and is somewhat similar to resistance in that it is used, in computing problems in distribution circuits, as a property of the individual conductor rather than the circuit as a whole. With single-phase circuits, for example, the total length of wire is used—not the length of the line; for three-phase the length per phase, etc.

For sine-wave, alternating-current, inductive reactance may be expressed as:

$$\text{Inductive reactance} = X = \frac{2\pi fL}{10^3} \text{ ohms per 1,000 ft. per conductor} \quad (52)$$

where

f = frequency in cycles per second.

Tables XI and XII give values of inductive reactance per 1,000 ft. of conductor for various standard conductor sizes and spacings and for 60- and 25-cycle current.

TABLE XI.—INDUCTIVE REACTANCE PER SINGLE CONDUCTOR IN OHMS PER 1,000 FT
60 Cycle, Copper or Aluminum, $\mu = 1$

Distance between centers of conductors, inches	Size of Conductors—B & S Gauge																
	Solid[1]							Stranded[1]									
	No 8	No 6	No 5	No 4	No. 3	No. 2	No 1	No 0	No. 00	No 000	No 0000	250M	300M	400M	500M	750M	1,000-M
⅜	0.0462	0.0409	0.0382	0.0356	0.0329	0.0303	0.0276										
½	0.0528	0.0475	0.0448	0.0422	0.0395	0.0369	0.0342										
1	0.0687	0.0634	0.0607	0.0581	0.0554	0.0528	0.0501	0.0464	0.0437	0.0411	0.0384	0.0365	0.0344	0.0311	0.0286	0.0250	
2	0.0846	0.0793	0.0766	0.0740	0.0713	0.0686	0.0660	0.0623	0.0596	0.0570	0.0543	0.0524	0.0503	0.0470	0.0445	0.0419	0.0377
4	0.1005	0.0952	0.0925	0.0899	0.0872	0.0845	0.0819	0.0782	0.0755	0.0729	0.0702	0.0683	0.0662	0.0629	0.0604	0.0568	0.0534
6	0.1097	0.1044	0.1018	0.0991	0.0964	0.0938	0.0911	0.0874	0.0847	0.0821	0.0794	0.0775	0.0754	0.0721	0.0696	0.0663	0.0628
8	0.1163	0.1110	0.1084	0.1057	0.1030	0.1004	0.0977	0.0940	0.0913	0.0887	0.0860	0.0841	0.0820	0.0787	0.0762	0.0727	0.0693
10	0.1215	0.1162	0.1135	0.1109	0.1082	0.1055	0.1029	0.0993	0.0966	0.0940	0.0913	0.0894	0.0873	0.0840	0.0815	0.0781	0.0746
12	0.1256	0.1203	0.1176	0.1150	0.1123	0.1097	0.1070	0.1033	0.1006	0.0980	0.0953	0.0934	0.0913	0.0880	0.0855	0.0823	0.0787
14	0.1291	0.1238	0.1210	0.1185	0.1157	0.1122	0.1104	0.1068	0.1041	0.1015	0.0988	0.0969	0.0948	0.0915	0.0890	0.0858	0.0823
15	0.1308	0.1255	0.1228	0.1202	0.1175	0.1148	0.1122	0.1084	0.1057	0.1031	0.1004	0.0985	0.0964	0.0931	0.0906	0.0874	0.0839
18	0.1349	0.1296	0.1270	0.1243	0.1216	0.1190	0.1163	0.1126	0.1099	0.1073	0.1046	0.1027	0.1006	0.0973	0.0948	0.0915	0.0881
21	0.1385	0.1332	0.1305	0.1278	0.1252	0.1225	0.1199	0.1159	0.1132	0.1106	0.1079	0.1060	0.1039	0.1006	0.0981	0.0949	0.0915
24	0.1415	0.1362	0.1336	0.1309	0.1282	0.1256	0.1229	0.1192	0.1165	0.1139	0.1112	0.1093	0.1072	0.1039	0.1014	0.0982	0.0947
30	0.1466	0.1413	0.1387	0.1360	0.1334	0.1307	0.1280	0.1243	0.1216	0.1190	0.1163	0.1144	0.1123	0.1690	0.1065	0.1025	0.1000
36	0.1508	0.1455	0.1428	0.1402	0.1375	0.1348	0.1322	0.1285	0.1258	0.1232	0.1205	0.1186	0.1165	0.1132	0.1107	0.1073	0.1042
42	0.1544	0.1491	0.1464	0.1437	0.1411	0.1384	0.1358	0.1321	0.1294	0.1268	0.1241	0.1222	0.1201	0.1168	0.1143	0.1109	0.1078
48	0.1574	0.1521	0.1494	0.1468	0.1441	0.1414	0.1388	0.1351	0.1324	0.1298	0.1271	0.1252	0.1231	0.1198	0.1173	0.1140	0.1108
60	0.1625	0.1572	0.1546	0.1519	0.1492	0.1466	0.1439	0.1403	0.1376	0.1350	0.1323	0.1304	0.1283	0.1250	0.1225	0.1192	0.1158
72	0.1667	0.1614	0.1587	0.1561	0.1534	0.1508	0.1481	0.1445	0.1418	0.1392	0.1365	0.1346	0.1325	0.1292	0.1267	0.1233	0.1202
84	0.1703	0.1649	0.1623	0.1596	0.1570	0.1543	0.1516	0.1480	0.1453	0.1427	0.1400	0.1381	0.1360	0.1327	0.1302	0.1270	0.1232
96	0.1733	0.1680	0.1653	0.1627	0.1600	0.1574	0.1547	0.1510	0.1483	0.1457	0.1430	0.1411	0.1390	0.1357	0.1332	0.1300	0.1268
108	0.1760	0.1707	0.1680	0.1654	0.1627	0.1601	0.1574	0.1538	0.1511	0.1485	0.1458	0.1439	0.1418	0.1385	0.1360	0.1320	0.1298
120	0.1784	0.1731	0.1705	0.1678	0.1651	0.1625	0.1598	0.1561	0.1534	0.1508	0.1481	0.1462	0.1441	0.1408	0.1383	0.1347	0.1322
132	0.1806	0.1753	0.1726	0.1700	0.1673	0.1646	0.1620	0.1583	0.1556	0.1530	0.1503	0.1484	0.1463	0.1430	0.1405	0.1375	0.1340
144	0.1826	0.1773	0.1746	0.1719	0.1693	0.1666	0.1640	0.1603	0.1576	0.1550	0.1523	0.1504	0.1483	0.1450	0.1425	0.1396	0.1360
156	0.1844	0.1791	0.1765	0.1738	0.1711	0.1685	0.1658	0.1621	0.1594	0.1568	0.1541	0.1522	0.1501	0.1468	0.1443	0.1411	0.1373
180	0.1877	0.1824	0.1797	0.1771	0.1744	0.1718	0.1691	0.1654	0.1627	0.1601	0.1574	0.1555	0.1534	0.1501	0.1476	0.1443	0.1412

[1] For stranded conductors the inductance will be approximately 0.0013 ohm less than for solid of the same size

TABLE XII.—INDUCTIVE REACTANCE PER SINGLE CONDUCTOR IN OHMS PER 1,000 FEET

25 Cycle, Copper or Aluminum $\mu = 1$

Distance between centers of conductors, inches	Size of Conductors—B & S. Gauge																
	Solid[1]							Stranded[1]									
	No 8	No. 6	No. 5	No. 4	No. 3	No. 2	No 1	No. 0	No 00	No 000	No 0000	250M	300M	400M	500M	750M	1,000-M
3/8	0.0192	0.0170	0.0159	0.0148	0.0137	0.0126	0.0115										
1/2	0.0220	0.0198	0.0187	0.0176	0.0165	0.0154	0.0143										
1	0.0287	0.0264	0.0254	0.0242	0.0231	0.0220	0.0209	0.0193	0.0182	0.0171	0.0160	0.0152	0.0143	0.0130	0.0119	0.0104	
2	0.0353	0.0331	0.0319	0.0308	0.0297	0.0286	0.0275	0.0259	0.0248	0.0237	0.0226	0.0218	0.0209	0.0196	0.0185	0.0170	0.0157
4	0.0419	0.0397	0.0386	0.0375	0.0363	0.0352	0.0341	0.0325	0.0314	0.0303	0.0292	0.0284	0.0275	0.0262	0.0251	0.0237	0.0221
6	0.0457	0.0435	0.0424	0.0413	0.0402	0.0391	0.0380	0.0364	0.0353	0.0342	0.0331	0.0323	0.0314	0.0301	0.0290	0.0276	0.0261
8	0.0485	0.0463	0.0452	0.0441	0.0430	0.0418	0.0407	0.0389	0.0378	0.0367	0.0356	0.0348	0.0339	0.0326	0.0315	0.0303	0.0288
10	0.0506	0.0484	0.0473	0.0462	0.0451	0.0440	0.0429	0.0413	0.0402	0.0391	0.0380	0.0372	0.0363	0.0350	0.0339	0.0325	0.0310
12	0.0524	0.0501	0.0490	0.0479	0.0468	0.0457	0.0446	0.0431	0.0420	0.0409	0.0398	0.0390	0.0381	0.0368	0.0357	0.0343	0.0327
14	0.0538	0.0516	0.0504	0.0494	0.0482	0.0472	0.0460	0.0446	0.0435	0.0424	0.0413	0.0405	0.0396	0.0383	0.0372	0.0358	0.0343
15	0.0545	0.0523	0.0512	0.0501	0.0490	0.0479	0.0467	0.0453	0.0442	0.0431	0.0420	0.0412	0.0403	0.0390	0.0379	0.0365	0.0350
18	0.0562	0.0540	0.0529	0.0518	0.0507	0.0496	0.0485	0.0469	0.0458	0.0447	0.0436	0.0428	0.0419	0.0406	0.0395	0.0381	0.0367
21	0.0577	0.0555	0.0544	0.0533	0.0522	0.0511	0.0500	0.0484	0.0473	0.0462	0.0451	0.0443	0.0434	0.0421	0.0410	0.0396	0.0382
24	0.0590	0.0568	0.0557	0.0546	0.0534	0.0523	0.0512	0.0497	0.0486	0.0475	0.0464	0.0456	0.0447	0.0434	0.0423	0.0409	0.0394
30	0.0611	0.0589	0.0578	0.0567	0.0556	0.0545	0.0534	0.0518	0.0507	0.0496	0.0485	0.0477	0.0468	0.0455	0.0444	0.0429	0.0414
36	0.0629	0.0606	0.0595	0.0584	0.0573	0.0562	0.0551	0.0535	0.0524	0.0513	0.0502	0.0494	0.0485	0.0472	0.0461	0.0447	0.0433
42	0.0644	0.0621	0.0610	0.0599	0.0588	0.0577	0.0566	0.0550	0.0539	0.0528	0.0517	0.0509	0.0500	0.0487	0.0476	0.0462	0.0458
48	0.0656	0.0634	0.0623	0.0612	0.0601	0.0589	0.0578	0.0563	0.0552	0.0541	0.0530	0.0522	0.0513	0.0500	0.0489	0.0476	0.0462
60	0.0677	0.0655	0.0644	0.0633	0.0622	0.0611	0.0600	0.0584	0.0573	0.0562	0.0551	0.0543	0.0534	0.0521	0.0510	0.0496	0.0483
72	0.0695	0.0673	0.0662	0.0650	0.0639	0.0628	0.0617	0.0602	0.0591	0.0580	0.0569	0.0561	0.0552	0.0539	0.0528	0.0513	0.0498
84	0.0710	0.0687	0.0676	0.0665	0.0654	0.0643	0.0632	0.0617	0.0606	0.0595	0.0584	0.0576	0.0567	0.0554	0.0543	0.0528	0.0513
96	0.0722	0.0700	0.0689	0.0678	0.0667	0.0656	0.0645	0.0629	0.0618	0.0607	0.0596	0.0588	0.0579	0.0566	0.0555	0.0541	0.0528
108	0.0734	0.0711	0.0700	0.0689	0.0678	0.0667	0.0656	0.0640	0.0629	0.0618	0.0607	0.0599	0.0590	0.0577	0.0566	0.0552	0.0540
120	0.0744	0.0722	0.0710	0.0699	0.0688	0.0677	0.0666	0.0650	0.0639	0.0628	0.0617	0.0609	0.0600	0.0587	0.0576	0.0562	0.0549
132	0.0753	0.0730	0.0719	0.0708	0.0697	0.0686	0.0675	0.0659	0.0648	0.0637	0.0626	0.0618	0.0609	0.0596	0.0585	0.0570	0.0557
144	0.0761	0.0739	0.0728	0.0717	0.0706	0.0694	0.0683	0.0668	0.0657	0.0646	0.0635	0.0627	0.0618	0.0605	0.0594	0.0579	0.0565
156	0.0769	0.0747	0.0736	0.0724	0.0713	0.0702	0.0691	0.0675	0.0664	0.0653	0.0642	0.0634	0.0625	0.0612	0.0601	0.0587	0.0572
180	0.0782	0.0760	0.0749	0.0738	0.0727	0.0716	0.0705	0.0689	0.0678	0.0667	0.0656	0.0648	0.0639	0.0626	0.0615	0.0602	0.0588

[1] For stranded conductors the inductance will be approximately 0.0006 ohm less than for solid of the same size.

Capacity.—Capacity, capacitance, or permittance is that property of an electric circuit whereby it holds an electric charge, as in the case of an electric condenser. Power circuits have capacitance between conductors (and also to ground but the latter is usually considered negligible in comparison with the former in power circuit problems). Capacitance is expressed in *farads* or *microfarads* $\left(\frac{farads}{1,000,000}\right)$ It is given by the equation

$$C = \frac{0.007353}{\log_{10} b/a} \text{ microfarads per 1,000 ft. per conductor,} \quad (53)$$

where

a = radius of conductor in inches.
b = distance between centers of conductors in inches.

This is *capacitance to neutral* for either single-phase or three-phase circuits. For unsymmetrical three-phase

$$b = \sqrt[3]{b_1 \times b_2 \times b_3}.$$

The measure of the opposition of a capacitance to the passage of an electrical current is called its "*capacity reactance*" or "*condensance,*" expressed in ohms.

For sine-wave alternating-current, capacity reactance =

$$X_c = \frac{10^6}{2\pi f C} \text{ ohms per 1,000 ft per conductor,} \quad (54)$$

where

f = frequency in cycles per second.

Since capacitance on a power circuit is between conductors (or is a shunt-circuit phenomenon), its effect is to cause a current to flow in addition to the normal power current, this current being the *charging current* necessary to charge that capacitance. Charging current is expressed by

$$\text{Charging current} = I_c = \frac{E_c}{X_c} = \frac{2\pi f C E_c}{10^6} \text{ amp. per conductor per 1,000 ft.} \quad (55)$$

$$E_c = \text{voltage to neutral} = \frac{E}{2} \text{ for single-phase,}$$

$$= \frac{E}{\sqrt{3}} \text{ for three-phase.}$$

On distribution circuits the voltages and distances are comparatively low and capacitance plays such a small part that its effect is usually neglected. Hence no tables will be given here for this quantity.

Voltage-Current Relations.—The relations between voltage, current, resistance, and reactance in simple circuits are given below:

Symbols . . . E = effective voltage in volts.
I = effective current in amperes.
R = resistance in ohms.
X = inductive reactance in ohms.
X_c = capacity reactance in ohms.
Z = impedance in ohms.

Resistance only, $E = RI$ (Fig. 158).

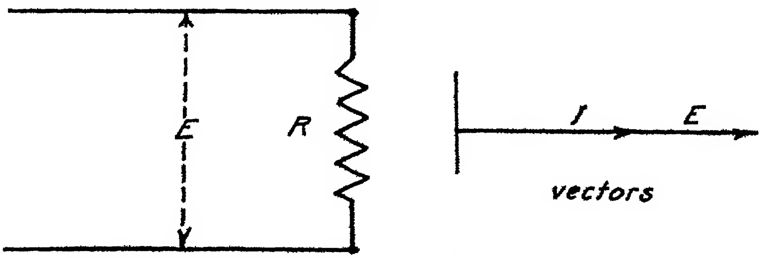


FIG. 158.—Circuit with resistance only

Inductive reactance only, $E = XI$ (Fig. 159)

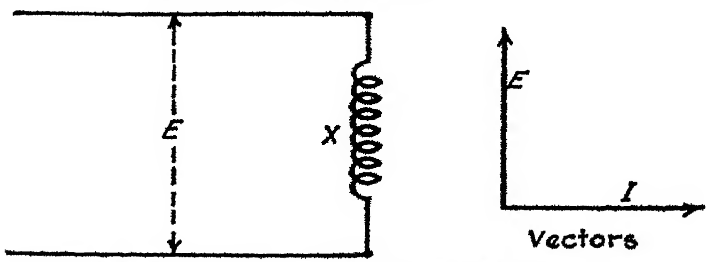


FIG. 159.—Circuit with inductive reactance only.

Capacity reactance only, $E = X_cI$ (Fig. 160)

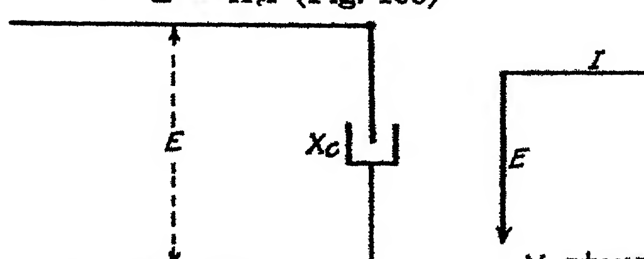


FIG. 160.—Circuit with capacity reactance only.

Inductive reactance and capacity reactance, $E = (X - X_c)I$ (Fig. 161).

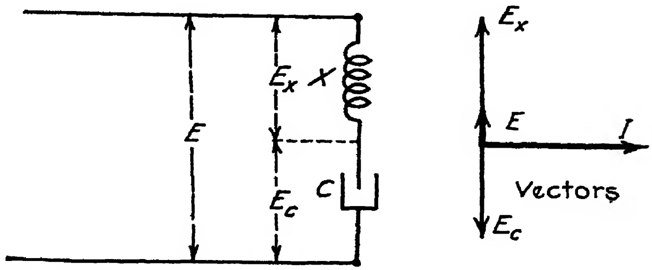


Fig. 161.—Circuit with inductive and capacity reactances in series.

Inductive reactance and resistance in series, $E = \sqrt{R^2 + X^2}\,I = ZI$ (Fig. 162).

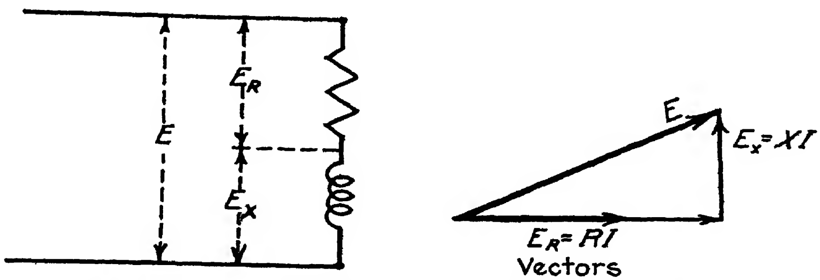


Fig. 162.—Circuit with reactance and resistance in series.

Two impedances in series, $E = \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}\,I$ (Fig. 163).

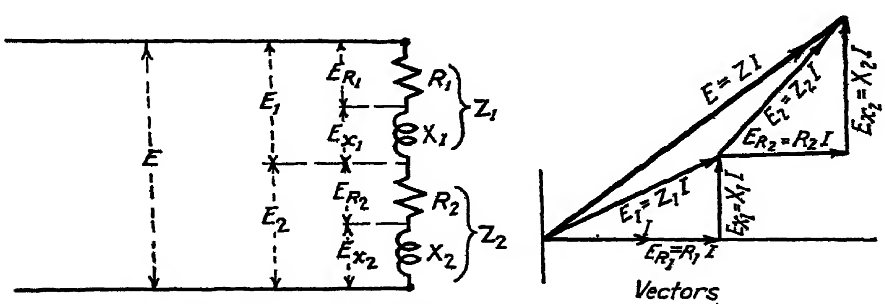


Fig. 163.—Circuit with impedances in series.

In general, where two or more resistances are in *series*, the total equivalent resistance is equal to their arithmetical sum

$$R = R_1 + R_2 + R_3, \text{ etc.}$$

Similarly where two or more reactances are in *series*,

$$X = X_1 + X_2 + X_3, \text{ etc.}$$

Hence for two or more impedances in *series*, the total impedance is

$$\begin{aligned} Z &= \sqrt{R^2 + X^2} \\ &= \sqrt{(R_1 + R_2 + R_3, \text{ etc.})^2 + (X_1 + X_2 + X_3, \text{ etc.})^2}. \end{aligned}$$

Where two or more resistances, reactances, or impedances are placed in parallel however, their reciprocals must be used in finding the equivalent values for the circuit as a whole.

The reciprocal of resistance is *conductance* = G.

The reciprocal of reactance is *susceptance* = B.

The reciprocal of impedance is *admittance* = Y.

These quantities are all expressed *mhos* and are represented by the symbols given above. It is sometimes convenient to think of these quantities as measures of the degree in which current is allowed to flow through a circuit in the same way that resistance, reactance, and impedance are measures of the degree of opposition to the flow of current through a circuit. The simple relations are as follows:

Resistances in parallel,

$$E = \frac{I}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{I}{G_1 + G_2 + G_3} = \frac{I}{G} \quad \text{(Fig. 164).}$$

or

$$I = EG.$$

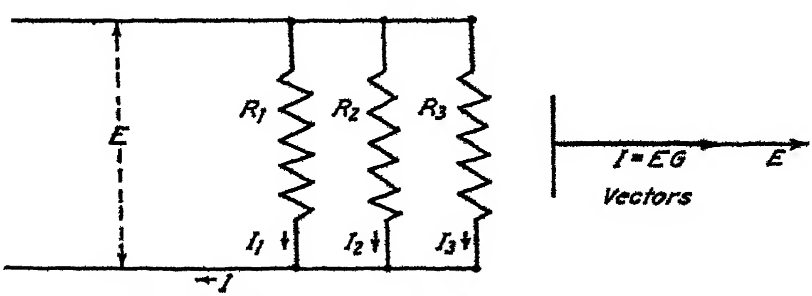


FIG. 164.—Circuit with resistances in parallel.

Reactances in parallel,

$$E = \frac{I}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3}} = \frac{I}{B_1 + B_2 + B_3} = \frac{I}{B} \text{ (Fig. 165).}$$

or

$$I = EB.$$

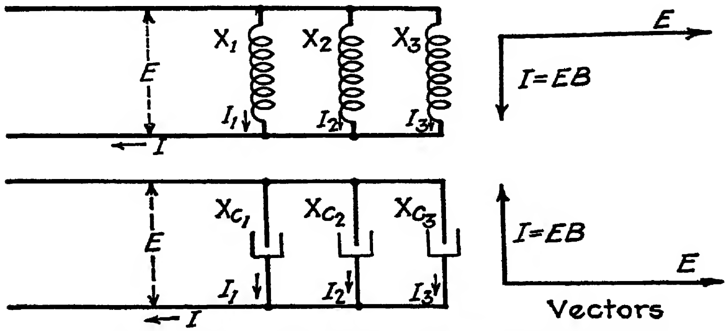


FIG. 165.—Circuit with similar reactances in parallel

If the reactances are dissimilar, *i.e.*, one capacity and one inductive,

$$I = E(B - B_c) \text{ (Fig. 166).}$$

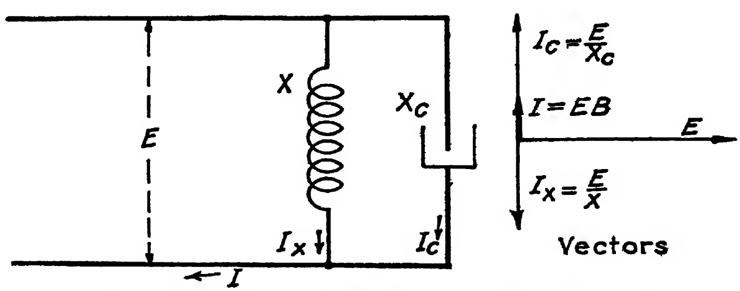


FIG. 166.—Circuit with dissimilar reactances in parallel.

Reactance and resistance in parallel,

$$E = \frac{I}{\sqrt{\frac{1}{R^2} + \frac{1}{X^2}}} = \frac{I}{\sqrt{G^2 + B^2}}$$

or

$$I = E\sqrt{G^2 + B^2} = EY \text{ (Fig. 167).}$$

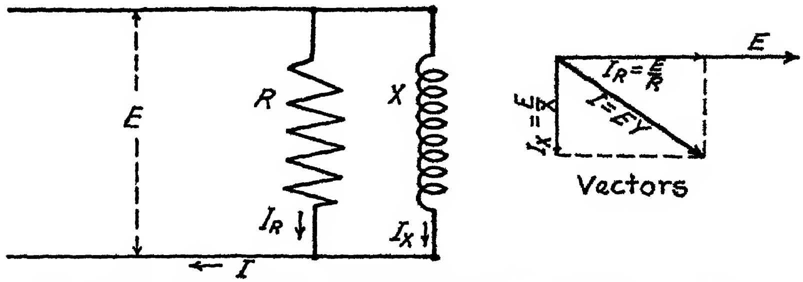


FIG. 167.—Circuit with resistance and reactance in parallel.

Two or more impedances in parallel,

$$I = E\sqrt{(G_1 + G_2)^2 + (B_1 + B_2)^2} \text{ (Fig. 168).}$$

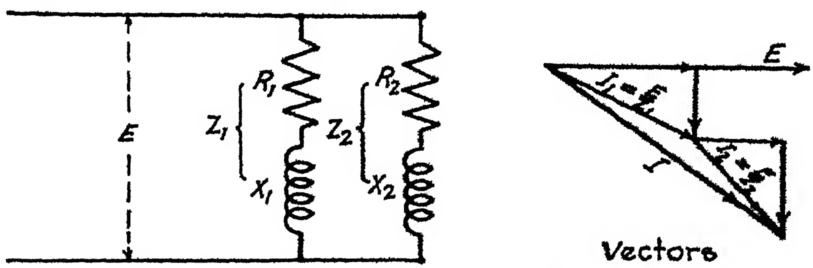


FIG. 168.—Circuit with impedances in parallel.

The simple relations of $G = 1/R$, $B = 1/X$ used above are true where the circuits concerned contain only R or X but not both. The general relationships are as follows, Fig. 169:

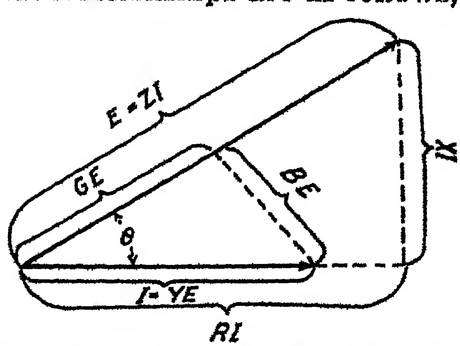


FIG. 169.—Relation between R, X, Z, G, B, and Y.

Consider a circuit with an impressed voltage $= E$ and a total current $= I$

$E = ZI$ may be replaced by two components, RI in phase with I and XI 90 deg. out of phase with I, that is, an equivalent circuit with R and X in series

$I = YE$ may be replaced by two components, GE in phase with E and BE 90 deg out of phase with E, that is, an equivalent circuit with G and B in parallel.

$$Z = \sqrt{R^2 + X^2}. \tag{56}$$

$$Y = \sqrt{G^2 + B^2}. \tag{57}$$

$$E = ZI = ZYE. \tag{58}$$

$$Y = \frac{1}{Z}. \tag{59}$$

$$\begin{aligned} GE &= YE \cos\theta. & RI &= ZI \cos\theta. \\ BE &= YE \sin\theta & XI &= ZI \sin\theta. \\ G &= Y \cos\theta. & R &= Z \cos\theta. \\ B &= Y \sin\theta. & X &= Z \sin\theta. \end{aligned}$$

$$G = Y\frac{R}{Z} = \frac{R}{Z^2} \tag{60}$$

If the circuit has R only (no X),

$$Z = R \text{ and } G = \frac{1}{R}$$

$$B = Y\frac{X}{Z} = \frac{X}{Z^2} \tag{61}$$

If the circuit has X only (no R),

$$Z = X \text{ and } B = \frac{1}{X}$$

$$R = Z\frac{G}{Y} = \frac{G}{Y^2}. \tag{62}$$

$$X = Z\frac{B}{Y} = \frac{B}{Y^2}. \tag{63}$$

These quantities apply to a circuit as a whole regardless of whether it is made up of parallel or series components, *i.e.*, R, X, Z, G, B, and Y apply to the circuit as a whole and not to any part. The relationships are useful, therefore, in dealing with impedances in parallel. For example, one of such impedances with R_1 and X_1 in series may be considered equivalent to $G_1 = R_1/Z_1^2$ and $B_1 = X_1/Z_1^2$ in parallel.

Similarly,

$$G_2 = \frac{R_2}{Z_2^2} \text{ and } B_2 = \frac{X_2}{Z_2^2}, \text{ etc.}$$

The equivalent circuit then consists of G_1, G_2, B_1, B_2, all in parallel and

$G = G_1 + G_2$, equivalent conductance of the circuit as a whole.

$B = B_1 + B_2$, equivalent susceptance of the circuit as a whole.

$Y = \sqrt{G^2 + B^2}$, equivalent admittance of the circuit as a whole.

These can then be converted into the characteristics of an equivalent series circuit, if desired, by

$$Z = \frac{1}{Y}.$$

$$R = \frac{G}{Y^2}.$$

$$X = \frac{B}{Y^2}.$$

The above may be summarized as follows:

A circuit with *several impedances in series*, carries the *same current* throughout, hence the *voltage* is equal to the vectorial sum of the component voltages necessary to pass that current through the various parts. The total *impedance* is, therefore, equal to the vectorial sum of the various impedances.

A circuit with *several impedances in parallel* has the *same voltage* applied across each of these, the total *current* being equal to the vectorial sum of the currents in the various paths. The total *admittance* is therefore equal to the vectorial sum of the admittances of the various paths.

Vectors and Complex Quantities.—Most problems in alternating currents involve the use of vectors to some extent. Vectors are used to represent both voltages and currents. Referring to Figs. 157 and 170, it may be seen that if OA is allowed to represent the maximum voltage E in magnitude, and the angle θ the time from the beginning of the cycle, the instantaneous values of the voltage at any time is given by the ordinate y_a. Similarly for currents.

A second voltage whose cycle starts somewhat before OA (a definite time or phase angle between corresponding parts on the two sine waves) may be superimposed on OA as shown by AB, Fig. 171. The sum of the two is then represented by the vector sum OB.

Figure 172 shows how current is represented by the vector I at a time angle θ_1 behind the voltage E_r and θ_2 behind the voltage E which equals $E_r + E_1$

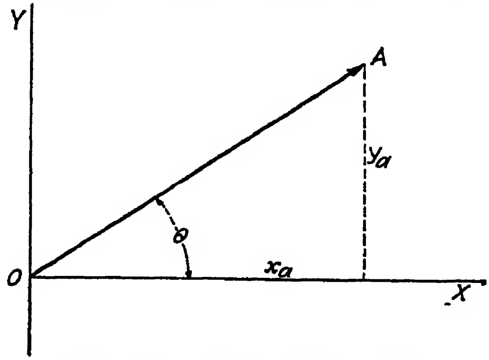


FIG. 170—Vector OA, angle θ.

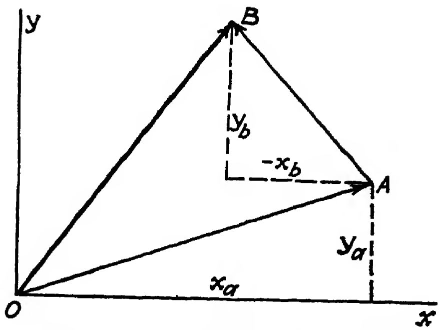


FIG. 171.—Addition of vectors.

In many problems vector quantities may be conveniently dealt with by use of their equivalent so called "complex quantities." In Fig. 173, the vector OA may be written

$$OA = x_a + jy_a,$$

which is merely a convenient form of expressing the rectangular components of OA, *i.e*, x_a on the horizontal axis and y_a on the vertical. The *imaginary* term j is the indication that y_a is the component at right angles to x_a. It is assumed to have the value of $\sqrt{-1}$ since

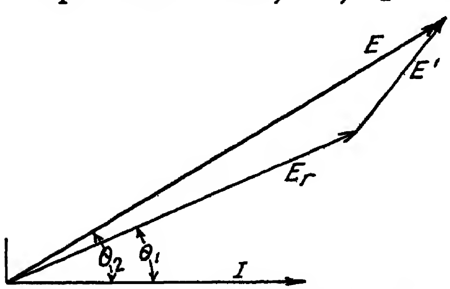


FIG 172.—Vectors for voltage and current.

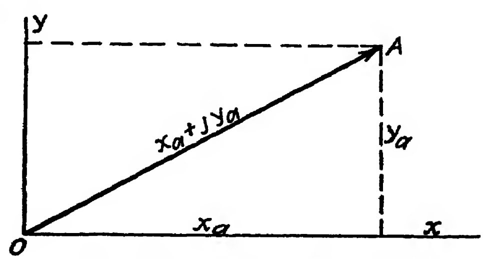


FIG. 173.—Complex quantity $x_a + jy_a$.

$jy_a = y_a$ at 90° to x_a.

$j^2y_a = y_a$ at 180° to x_a or in the same direction but the opposite sense.

$$j^2y_a = -y_a.$$

$$j^2 = -1.$$

$$j = \sqrt{-1}.$$

Complex quantities may be treated as algebraic quantities, added, subtracted, multiplied, and divided:

$$(x_a + jy_a) \text{ plus } (x_b + jy_b) = (x_a + x_b) + j(y_a + y_b), \text{ Fig. 174} \qquad (64)$$

$$(x_a + jy_a) \text{ minus } (x_b + jy_b) = (x_a - x_b) + j(y_a - y_b), \text{ Fig. 175} \qquad (65)$$

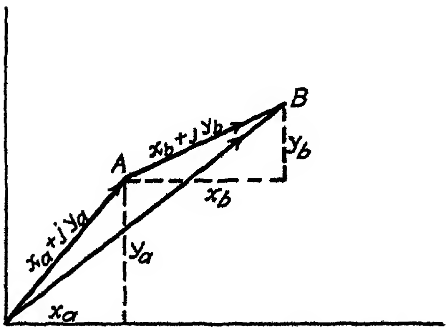


FIG. 174.—Addition of complex quantities.

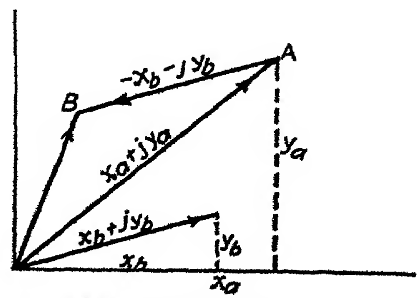


FIG. 175.—Subtraction of complex quantities.

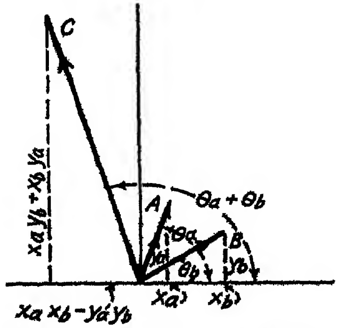


FIG. 176.—Multiplication of complex quantities.

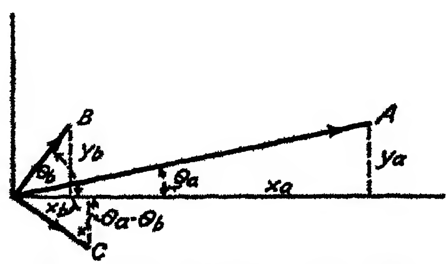


FIG. 177.—Division of complex quantities.

$(x_a + jy_a)$ multiplied by $(x_b + jy_b)$

$$= x_ax_b + j(x_ay_b + x_by_a) + j^2y_ay_b$$

$$= x_ax_b - y_ay_b + j(x_ay_b + x_by_a), \text{ Fig. 176.} \qquad (66)$$

$$(x_a + jy_a) \text{ divided by } (x_b + jy_b) = \frac{x_a + jy_a}{x_b + jy_b} \times \frac{x_b - jy_b}{x_b - jy_b}$$

$$= \frac{x_ax_b + y_ay_b + j(x_by_a - x_ay_b)}{x_b^2 - j^2y_b^2}$$

$$= \frac{x_ax_b + y_ay_b + j(x_by_a - x_ay_b)}{x_b^2 + y_b^2}, \text{ Fig. 177.} \qquad (67)$$

PART II
MECHANICAL DESIGN

CHAPTER XV

MECHANICAL DESIGN

The term "*mechanical design*" is here used to refer to the consideration of what might be called the physical elements of the distribution system. Whereas "*electrical design*" dealt with the types of electrical circuits, voltages, service requirements, electrical loads, etc., mechanical design concerns itself with the structures on which those circuits are carried and their arrangement with regard to the surrounding physical conditions. It involves study of materials of construction, strength of such materials in the various forms in which they may be utilized, stresses to be encountered, advisable relationships between probable stresses and strengths to oppose them, considerations of safety to life, property, and good service, relationships with the property of other utilities, etc.

Proper mechanical design is one of the chief factors in maintaining good service to customers. A large majority of interruptions to service are traceable to physical failures on the distribution system, broken wires, broken poles, damaged insulation, damaged apparatus, etc. Of course many of these are more or less unavoidable, being the result of unexpected occurrences in Nature, unusually severe storms, lightning, interference by unauthorized persons, and the like, also undetected flaws in material or workmanship. Their number can be very greatly reduced however, if careful attention is paid to designing and constructing the various physical parts to withstand, with reasonable safety factors, not only normal conditions but also a fair degree of probable abnormal occurrence. It is also of equal importance that the system be maintained in as good condition as possible and not be allowed to deteriorate beyond a reasonable degree of safety. As a rule, the maintenance required is more or less in inverse proportion to the excellence of the original construction.

It is almost axiomatic that ultimate economy is the accompaniment of good construction since excessive maintenance or unduly

short life can very easily more than overbalance a saving in first cost. However, there is, naturally, a limit to what it is advisable to expend for extra strength or probable extra long life of materials. Where there are so many variables in the surrounding conditions, both as to probable stresses and also as to strength of structures, as is found in these problems, a reasonable amount of extra expenditure for additional strength is a good investment. This can easily be carried too far, however, and money be spent for excessive safety factors, far beyond what experience shows have ever been needed. It is a problem requiring good engineering, including a considerable amount of good judgment, to determine where the line should be drawn between economy and safety. It is not good engineering to spend blindly for additional safety factors all the money which a trusting management can be induced to appropriate, on the theory that a failure, even if only remotely possible, would react unfavorably toward the designer, whereas if no failure occurs the waste would never be detected. The probabilities of failure should be carefully studied and sufficient provision made to insure against frequent occurrence, but it should be recognized by all concerned that insurance against every possibility is almost impossible and attempts even to approach such insurance are usually very expensive and very likely to be unjustified by the requirements of the service.

In designing a system, or a line, or a structure, it should be borne in mind that the whole is no stronger than its weakest part. An ideal design would be one where each constituent part had the same proportion of strength to probable stress as every other part, taking account of course of all variable conditions of loading, deterioration with age, etc. For example, it is uneconomical to spend extra money for additional strength in a bolt when it is already much stronger, relatively, than the parts which it joins. There is sometimes a tendency to analyze a failure of a structure by attributing the cause to one particular member and increasing the strength of that member accordingly without regard to others. This is likely to result in not only an unnecessary increase in cost of construction but also in actually weakening the structure by placing additional stresses on other already weaker members. Close and accurate observation, consideration of all affecting factors, and in many cases confirmation by additional failures or by laboratory or field tests should be awaited before changing a

design which has been carefully worked out and has given reasonably good service.

There are no universally accepted standards of design for materials or structures for use in building a distribution system. The Overhead Systems Committee of the National Electric Light Association have from time to time proposed tentative standards for the more commonly used materials.[1] Most companies use some of these standards and it would be no doubt desirable if they, or revisions of them, could all be generally adopted. At present, however, there are a great many divergences from the proposed standards which are almost as commonly used as the standards themselves and these can probably be eliminated only by a realization of economy in the use of the standards

In 1915, the first edition of the "National Electrical Safety Code" was published by the U. S. Bureau of Standards. This code was prepared with the collaboration of the various interests concerned—power, telephone, telegraph, railway, etc.—and was intended to be a codification of recommended practice. Its provisions were, for the most part, intended to set forth minimums which were considered requisite for safety. Naturally there were many points of disagreement among the various interests in this first Code, leading to revisions in 1916 and again in 1920 In 1927, another edition was brought out again revising the text and rearranging it in a more convenient form. There are still many points which have not been universally accepted and it is to be expected that another revision will be made before many years.

This code, however, represents the nearest approach to a national standard which exists and, in spite of certain imperfections, it forms the basis and reference standard for a greater part of the construction practice throughout the country. In many states the Code has either been adopted or has been used as a basis for mandatory regulations applying to all construction in the state. A careful study of this code is recommended to all engineers who have or expect to have to deal with the construction of distribution systems. The application of its provisions to certain parts of the construction will be quoted from time to time in the following chapters, it being referred to generally as "the Safety Code."

[1] Overhead Systems Reference Book, N.E.L.A.

In designing structures for supporting overhead lines, two very indeterminate factors are encountered. The first is the maximum loading which is likely to be imposed. The National Electrical Safety Code defines three degrees of loading as follows:

Heavy Loading—That due to ½-in. radial thickness of ice on all conductors, plus 8 lb. per square foot horizontal wind pressure on all exposed surfaces (projected area for cylindrical surfaces), at 0°F.

Medium Loading.—That due to ¼-in. radial thickness of ice on all conductors plus 8 lb. per square foot wind pressure on all exposed surfaces (projected area), at +15°F.

Light Loading.—That due to 12 lb. per square foot wind pressure on all exposed surfaces (projected area), at + 30°F.

The Code also indicates a division of the country into definite zones in which it is intended that these loadings be assumed as maximum. There are, however, many localities in each of these zones where the loading assigned is not at all applicable Mountain regions in the light-loading area may expect to experience heavy loading, etc. The Code recognizes this in providing that the prescribed loading for any locality may be defined by administrative authority. There is considerable doubt, however, whether the heavy loading assigned to the greater portion of this country is not more severe than is warranted by experience. It is recognized that more than ½-in. radial thickness of ice is quite often encountered. It is also known that winds of higher velocity than those causing 8 lb. per square foot pressure (about 60 miles per hour) are not uncommon. It is believed, however, that the combination of ½-in. ice and 8 lb. pressure at the same time is a rare occurrence in most localities, so rare indeed that it might be considered in the same catagory as cyclones and other disasters, against which it is almost impracticable to provide in ordinary construction. There are no doubt certain localities of limited extent where this heavy loading is a reasonable figure for design and there are no doubt some places where even heavier would be justified. It is quite probable, however, that for the greater part of the so called "heavy-loading" district as defined in the code, some revision of the loading requirements will be found practicable. It is possible that it may take the form of an increase in ice loading and a decrease in wind loading, or possibly a decrease in both. The Overhead Systems Committee of the National Electric Lighting Association has been collecting

data on this subject for several years and some more definite information on the probable worst loading will no doubt soon be available. At present, however, the Code's provisions are those most generally accepted and are included in state regulations in a number of places, so they will be used here.

The second indefinite quantity is the action of structures under stress when elasticity and other similar factors are taken into account. The usual assumption in designing distribution structures is to assume all the parts to remain rigid. It is well known of course that this is far from the case. Poles bend, wire stretches, soil bearing "gives," etc. Loading, which is assumed to be uniformly applied, is rarely so and it is quite probable that the slight "giving" here and there materially reduces the stresses on individual members below the values indicated by computation under the assumption of rigid structures. Another factor of some uncertainty is the composite action of different materials such as wood and steel when associated in the same structure. It is likely to be quite different from that of each material or part tested separately. As a general rule, in investigating the strength and probable action of such structures, satisfactory information can be gained only by tests on full-sized samples, simulating field conditions, and field loading as far as possible. Such a test on a full-sized distribution line to determine actual stresses in conductors, poles, guys, etc., under known wind and ice loading is now being carried forward by the Overhead Systems Committee of the National Electric Lighting Association and the results obtained will no doubt do much to correct our ideas of the proper assumptions to be made in designing pole lines.

In continuing with the more detailed consideration of the various features of mechanical design on the distribution system, it is assumed that the reader has a working knowledge of the fundamental principles of structural design. A brief review of some of the most important ones will be found in Chap. XXX.

CHAPTER XVI

POLES

By far the greater majority of distribution circuits in this country are overhead lines, carried on poles and, for the most part, wooden poles. When it is realized that the cost of the pole itself in place may represent something like 40 to 50 per cent of the total cost of the line, it is evident that the material, strength, location, spacing etc., of these poles are matters which warrant careful consideration.

One of the major factors producing the large and rapid increase in use of electrical energy here has been the universal employment of overhead wooden pole lines. If underground distribution had been the rule, the cost would have been so much higher and the rates necessary also higher that growth of systems into the less densely populated and outlying territories would have been seriously retarded. Also, the greater ease and rapidity with which overhead pole lines can be installed as well as the smaller investment required have been contributory causes to the great development which has been and is being experienced. This fact should be remembered when complaints are heard of the comparative unsightliness of overhead pole lines.

There is no denying that overhead pole lines are rarely if ever things of beauty. They cannot at best be said to add much to the good appearance of a street or road along which they are located. Their retention is merely an economic necessity resulting from the demand for electric service at moderate cost. When the line is poorly built or poorly maintained the objectionable features are increased. The poles, being the most obvious part of the construction, have a large bearing on the appearance of the line. Crooked or misshapen poles or good poles crookedly set are anything but an asset, whereas a straight, well-graded line of well-shaped poles has at least the virtue of appearing neat and workmanlike, which is itself an element of beauty.

The chief types of timber which are used for wooden poles are Western Red or Idaho cedar, Northern White, Eastern or Michi-

gan cedar, chestnut, and Southern pine. Other woods are used to some extent but the greater bulk of poles are of the above four varieties.

Western Red cedar poles are, as a rule, comparatively straight and of a uniform taper. This taper is not large, being of the order of 1 in. in 7 or 8 ft. They are usually relatively smooth and free from knots, etc. These qualities give them a good appearance when set in a lead. The sapwood on the outside of the pole is comparatively soft which is very favorable to climbing with spurs. The wood is durable as compared with most other woods, especially for above-ground or below-ground conditions. It is subject to decay at the ground line however (as is any other wood) and, although more desirable than many other varieties even under these conditions, it is usually advisable to use some form of preservative treatment to prolong its life at this point. The wood is comparatively light, making the poles easier to handle than some of the other types. On account of the small taper, the butts are not large, even on large poles, hence a moderate sized hole is sufficient for setting them. The wood has a relatively high strength compared with other woods, being only second to yellow pine of those commonly used for pole timber. Western Red cedar comes mostly from Idaho, Washington, Oregon, and British Columbia. Although used in very large quantities, especially in the western and northern parts of the country, there are still large resources available in this species.

Northern (or Eastern) White cedar poles were formerly used quite extensively in the northern states, especially in the region in which they are native, *i.e.*, Michigan, Wisconsin, Minnesota, and the adjacent regions of Canada. Their use has become rather limited, however, due to two chief causes. The supply has been greatly diminished for one thing. Also, on account of their relatively large taper and tendency to flare at the butt, they are much harder to handle and set than Western cedar or pine poles, especially in the larger sizes. They are inclined to be knotty and not very straight, hence do not present the best appearance when set. The wood is very durable however. In the smaller sizes (up to 35 ft.) they are still used to quite an extent, in the Great Lakes Region especially. Butt treatment is effective in prolonging their life, retarding decay at the ground line. Above and below ground, the wood usually has a fairly long life untreated. They are easy to climb due to the soft sapwood and

are also relatively light to handle. The unit strength of the timber is less than that of Western cedar or pine but the fact that the taper is greater makes a Northern cedar pole somewhat stronger over all than a Western Red cedar pole of the same top diameter, its butt being considerably larger.

Chestnut poles were formerly native to most of the states east of the Mississippi River and were largely used for distribution construction. The blight has greatly reduced the supply and they now come chiefly from the Southeastern states and in greatly diminished quantities. The chestnut pole is relatively durable without treatment (except at the ground line as with other woods) and is comparatively strong, being about equal to Western cedar. The poles are more like Northern cedar in appearance however, being inclined to be knotty and crooked, which is detrimental to the good appearance of the line. They are somewhat harder to climb than the cedars, the outside wood being harder and they are also much heavier. They have the characteristic of being "hotter" poles than the cedars, *i.e.*, their resistance to the passage of electric current is somewhat less.

Southern yellow pine has had a greatly increasing use as a pole timber during the past few years, partly on account of its favorable characteristics and partly due to the reduction in available supply of other timbers. There are several different varieties of southern yellow pine which vary considerably in strength, the long-leaf variety being the strongest. Since it is very difficult to distinguish between varieties after the pole is cut (and especially if it is treated) the allowable strength must usually be based on that of the weaker varieties. Nevertheless, it is the strongest of the four woods here described. The poles are characteristically straight and free from knots, making a very good appearance in a lead. The taper is slight, being even less than western cedar which makes the butt comparatively small for a given top diameter. The greater unit strength of the wood tends to compensate for this if top diameter is used as a criterion. The wood is very hard compared with cedar, which makes the poles more difficult to climb. The wood is the least durable when untreated of any of the species considered, it being usually considered impracticable to use pine poles unless treated for their whole length. When so treated their durability is very good, being claimed to be considerably greater than that of the cedars. The evidence so far is not very conclusive as to just what life may be expected.

Average Characteristics of Various Timbers.—The table below gives average figures in regard to some of the characteristics of the four types of poles mentioned.

TABLE XIII

Timber	Weight in pounds per cubic foot	Taper, increase in diameter per 10-ft length, inches	Pounds per square inch bending, National Electric Safety Code	Recently proposed values[1]
Western Red cedar	23 1	1 0 to 1 5	5,000	5,600
Northern White cedar	23 1	1 5 to 2 0	3,600	3,600
Chestnut	41 2	1 5 to 2	5,000	6,000
Southern yellow pine	32 to 38	0 75 to 1 5	6,500	6,800
Cypress	28 7		5,000	4,800
Redwood	24 2		3,600	4,400

[1] The increased values for unit strengths shown in this column have been proposed for general adoption as the result of some more recent tests They have not been approved as yet by the U S Bureau of Standards or the N E.L A

Pole Defects.—All species of poles are subject to certain defects. Some of these are not very objectionable and must be overlooked in buying poles in commercial quantities. Others seriously impair the strength of the pole and should not be allowed.

Decay may attack the pole timber in three ways. *Butt rot* may start at the center of the trunk of the tree and work upward slowly through the heart. It usually ceases when the tree is cut and set as a pole and hence is not a serious defect unless it occupies a fairly large proportion of the butt area or extends a long way into the butt. Additional overall diameter should be required if the butt rot is of any considerable extent. *Heart rot* may start from a dead branch stub or scar and extend into the heart of the tree, working upward and downward. It is a serious defect, weakening the pole, and poles showing it should not be used ordinarily. The *outside or sapwood* is subject to rot if the bark is removed or if the log is left on the ground any considerable length of time. The same effect occurs at the ground line of a pole after it is set, where it is subject to alternate wet and dry conditions. If at all extensive, it is a serious defect, the pole being weakened proportionally.

Insect damage is likely to occur to any pole before or after it is set, by insects entering the pole through checks, knot holes,

etc., and working in its interior. Often there is no external evidence of such a defect. Probably the worst offender in this regard is the white ant or termite. This insect is found in various parts of the country and its prevalence seems to be spreading. Termites are of two general varieties, one which works underground or near the ground and one which flies and attacks higher parts of the pole. The latter type has so far confined its activities mostly to the warmer southern localities. It works entirely on the interior of the pole, channelling and disintegrating the wood until the pole may become a mere shell. Treatment of the pole with creosote is employed to discourage this pest and is reported to be quite effective. Full-length treatment of the pole is necessary however (as is usual with pine poles if the aerial type is prevalent as butt treatment does not prevent attacks on the upper part of the pole.

Checks (radial cracks due to seasoning) and *shakes* (circular splits between wood fibers due to strains in felling, handling, etc.) are defects which are common and may be serious weaknesses if of considerable extent.

Knots, if sound and not too large or numerous, and *cat faces,* if sound, are not considered serious defects.

Seasoning of timber before it was used for poles was at one time considered important. It still is, if preservative treatment is to be applied. Otherwise there is apparently little difference whether the pole is seasoned before it is set or is allowed to season in place. If it is to be treated, it is important that a greater part of its moisture is removed by seasoning to allow the impregnating compound to enter the fibers of the wood.

Decay and Preservative Treatment.—As has been mentioned above, all wood poles are particularly subject to decay at the ground line, and some, such as pine poles, are also quite subject to it elsewhere. Decay is due to a living plant organism (fungus) which attacks and digests the wood fiber leaving a dead substance of no strength. The conditions most favorable to the growth of decay fungi are air, moisture, and heat, together with food supply of course. In the section of the pole below the ground line moisture is usually present but air is lacking. In the part above the ground-line air is present but moisture is lacking, except at occasional intervals. In the portion at the ground line and for a few inches below that point, both of these elements are present for a greater part of the time and hence this particular section is especially subject to decay.

In order to retard or prevent decay it is necessary either to remove the conditions favorable to its development or else to poison the food supply so that it will not support its growth. The former method appears impracticable with wood poles. The latter is accomplished by various forms of preservative treatment. The necessary qualities of such a treatment are, first, that it poisons the wood against its use as food for decay fungus, second, that it is of such a nature that it may be injected into the wood to such a depth as to be beyond the point ordinarily reached by the spores of the decay fungus, and third, that it be of sufficiently permanent nature that it will not evaporate or leech out of the wood, having then only a temporary effect.

The most commonly used preservative at the present time is creosote. With poles such as cedar which are relatively durable above the ground line, treatment is usually applied only to the butt end of the pole, that is from the extreme butt to a point which will be about 2 ft. above the ground line when the pole is set. Full-length treatment, even on cedars, is sometimes used however for the purpose of resisting insect attacks (white ants, etc.). The most usual form of treatment is what is known as the *B* treatment (as distinguished from *AA* treatment which employs only a 15 min. dip in hot creosote). The poles are placed in hot (230°F.) creosote for several hours then removed and placed in a bath of cold creosote, the exact duration of each immersion depending on the seasoning of the wood and other factors. The theory is that the pores of the wood and the air contained in the cells are expanded in the hot bath (and also some of the moisture contained is expelled) and the creosote in the cold bath is then drawn in when these contract. A thorough preliminary seasoning is an important factor in this treatment especially if perforation is not employed. The latter is now quite extensively used, however, in connection with this form of treatment. The surface wood for some distance above and below the probable ground line is punctured by steel points or wedges. The purpose is to form channels by which the creosote may more readily penetrate into the wood. This is especially necessary with so-called "case-hardened" poles, *i.e.*, a certain percentage of poles which have a relatively impenetrable shell on the outside, and also poles which are imperfectly seasoned. It is claimed that the perforation method accomplishes better results in increased durability with poles which have been seasoned only a short

time than the *B* treatment without perforation does with poles seasoned a year or more. It cannot be said that this claim is thoroughly established as yet however. As a rule a ½ in. depth of penetration of creosote is desirable and is easily obtainable with the perforation method.

Southern yellow pine poles require treatment for their full length. Two types of treatment generally used are called the "full-cell treatment" and "empty-cell treatment." In the former, the timber is placed in a large cylindrical tank and steamed under pressure, after which a vacuum is drawn to remove the condensed steam and sap moisture. Creosote oil is then run in and put under high pressure to force it into the cells of the wood. This gives a deep impregnation and leaves the cells full of creosote. In the empty-cell treatment a preliminary air pressure is applied, the creosote is applied under high pressure, after which the pressure is removed and a vacuum drawn which removes the excess creosote, leaving the cells empty but coated with creosote. Yellow-pine poles thus treated are no doubt comparatively durable. The full-length treatment makes them somewhat dirty to handle and to climb, which is sometimes considered a serious objection. The empty-cell treatment goes a long way toward removing this objection however.

The application of creosote with a spray or brush has been used to some extent (so-called "brush treatment"). The penetration thus gained is so slight that this method has not proved effective to any large degree. An adaptation of the method has been recently applied to old, untreated poles, in place, with some success. Hot creosote is sprayed on the ground-line section of the pole under high pressure, the wood being first cleaned of any decay and sometimes charred.

Other types of treatment have been used to some extent but none of them have as yet reached any where near the volume of the creosote treatments for poles. Several kinds of salts such as zinc chloride, mercuric chloride, copper sulphate, etc. have been found more or less effective, but for the most part they are soluble and hence relatively impermanent. What appears to be a very basic study of the fundamentals of the problem of decay and preservative treatment has recently been made by L. P. Curtin of the Engineering Laboratories of the Western Union Telegraph Company. He claims that the digestion of wood substance by fungus growth is almost invariably preceded by the creation

of an acid condition, which prepares the wood for assimilation. This leads to the theory that a preservative substance which is relatively insoluble in water (not leeching out of the wood) but is soluble in acid would be ideal. Several such substances are available, the most favorable appearing to be zinc metarsenite. Laboratory experiments seem to have demonstrated its worth but this has not yet been verified by extensive actual experience.

Probably the best evidence available of the value of treatment of pole timber in prolonging the life of poles in actual use is given in the report on "Service Tests of Treated and Untreated Poles[1] Results of test lines in several different parts of the country are given. Some of the more important features are summarized below:

Warren-Buffalo Line of American Telegraph and Telephone Company after 20 to 21 years

	Number of poles in test	Sound, per cent	Partly decayed, per cent	Removed on account of decay, per cent
Chestnut				
Untreated	525	0	81 2	18 8
Brush treated, one coat	100	0	88	12
Brush treated, two coats	315	16.2	79	4 8
Open-tank treated	175	81	19	0

Omaha-Denver Line of American Telegraph and Telephone Company after 16 years

Chestnut:				
Untreated	176	0	6.2	93.8
Brush treated, two coats	182	0 6	29 6	69.8
Open-tank treated	175	48	41 1	10.9
Northern cedar:				
Untreated	92	0	4 3	95.7
Brush treated, two coats	169	6	26.6	67.4
Open-tank treated	157	90 5	7.6	1 9

[1] *Serial report, Pub.* 278–3. Overhead Systems Committee, N.E.L.A., October, 1927, and *Pub.* 25–17, N.E.L.A., R. M. Wicha, U. S. Forest Products Laboratory, Madison, Wis.

Savannah-Meldrum Line of American Telegraph and Telephone Company after 16 Years

	Number of poles in test	Sound, per cent	Partly decayed, per cent	Removed on account of decay, per cent
Chestnut:				
Untreated	202	0	25.7	74.3
Brush treated, one coat	35	0	25 6	74.4
Brush treated, two coats	114	0	52 7	47 3
Southern White cedar.				
Untreated	197	0	3 8	96 2
Brush treated, one coat.	39	0	2 5	97 5
Brush treated, two coats	118	0	14 3	85.7
Poles in and around Los Angeles after 16 Years				
Western red cedar.				
Untreated	32	0	46.9	53 1
Brush treated	60	5	48.3	36 7
Open-tank treated	244	75.4	22.5	2 1

In the above, the open-tank treatment was all done with creosote (for the figures given). The brush treatment was with various materials, creosote, carbolium, tar, etc., but the results did not vary widely for these. Some of the poles were set green and some seasoned but the results did not seem to be consistent in this regard so they are not given separately. The figures given are only totals and the reports referred to should be consulted for further details in regard to treatment, etc. The points which it is wished to bring out are the very evident prolongations of life by the open-tank treatment. Brush treatment, while somewhat effective, does not compare in effectiveness with the open-tank. Two brush coats are apparently somewhat better than one.

Size and Classification.—The height of pole to be used in any particular location depends on several factors such as:

1. Length of pole space to be occupied by wires and other equipment.
2. Clearance above ground required or desired for wires and other equipment.
3. Clearance required or desired above obstructions to be crossed such as trees, buildings, wires and poles of other utilities.
4. Height above ground (or obstructions) necessary to allow branch circuits, such as service drops, to be taken off.
5. Regulations of local authorities.

Probably the most commonly used pole for general distribution purposes is the 35-ft. pole. This ordinarily fulfills very well the requirements for clearance above ground and height for taking off services, etc., with a moderate number of wires. Thirty-foot poles are also used to considerable extent, especially for rural lines. Poles smaller than 30 ft. are not commonly employed for distribution lines. The larger sizes (40 ft. and longer) are, of course, used for providing clearance over obstructions, for heavier leads, etc. In some cities it is found advisable to use nothing smaller than 40-ft. poles on account of the frequent necessity for additional clearances Where joint use of poles with communication circuits is practiced, higher poles are often required Naturally, economy points to the use of as small a pole as will meet the requirements but it should be kept in mind that a little additional investment in pole length originally may sometimes obviate a considerable amount of maintenance work later on. Data on clearances as required by the Safety Code is given in Chap. XXII, on "Conductors." Where a pole which is taller than the remainder of the poles in the lead is used to clear a tree or other obstruction, it is customary to grade the line on both sides up to the tall pole, in steps of not over 5 ft. per span. This is not entirely necessary from the standpoint of strength or convenience as a rule, but it adds to the good appearance of the line. On rural lines, grading is often omitted or done in larger steps.

The diameter of pole to be used is gauged largely, of course, by the strength required, which is discussed more fully below. For the ordinary line pole (not guyed) the critical point of strength is at or near the ground line, hence the diameter at that point is an important factor. Where a pole is guyed, however, the diameter at the point of attachment of the guy is the measure of its strength. The requirements for framing (attaching cross-arms, etc.) and working on a pole, impose a minimum limit on the diameter of the top—somewhere about 6 in. is usual. In order to facilitate the selection of poles to meet these requirements, methods of classification have been applied to the different species. The poles are divided into several classes according to top diameter (or circumference), and the diameter 6 ft. from the butt (approximately the ground line) for each length is also given. Thus all poles in a given class (Class B for example) regardless of length, should have approximately the same strength

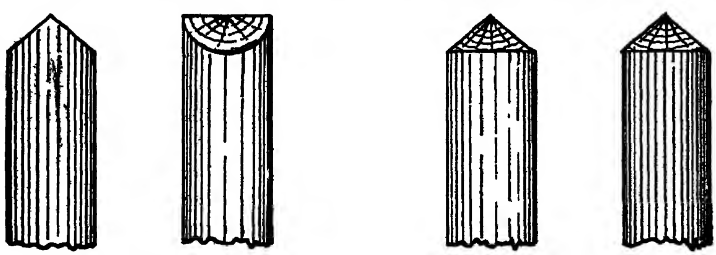
TABLE XIV

Western Red Cedar Poles and Guy Stubs (Minimum Circumferences of Poles in Inches)

	Class A		Class B		Class C	
Length, feet	Top	6 ft. from butt	Top	6 ft. from butt	Top	6 ft. from butt
20	28	30	25	28	22	26
22	28	32	25	30	22	27
25	28	34	25	31	22	28
30	28	37	25	34	22	30
35	28	40	25	36	22	32
40	28	43	25	38	22	34
45	28	45	25	40	22	36
50	28	47	25	42	22	38
55	28	49	25	44	22	40
60	28	52	25	46	22	41
65	28	54	25	48	22	43
70	28	56	25	50		
Northern White Cedar Poles (Minimum Circumferences of Poles in Inches)						
20	24	33	22	29	18¾	27
22	24	34	22	30	18¾	28
25	24	36	22	32	18¾	30
30	24	40	22	36	18¾	33
35	24	43	22	38	18¾	36
40	24	47	22	43	18¾	40
45	24	50	22	47	18¾	43
50	24	53	22	50	18¾	46
55	24	56	22	53	18¾	49
60	24	59	22	56		
Chestnut Poles (Minimum Circumferences of Poles in Inches)						
25	..	.	..	..	20	30
30	24	40	22	36	20	33
35	24	43	22	40	20	36
40	24	45	22	43	20	40
45	24	48	22	47	20	43
50	24	51	22	50	20	46
55	22	54	22	53	20	49
60	22	57	22	56		
65	22	60	22	59		
70	22	63	22	62		
75	22	66	22	65		
80	22	70	22	69		
85	22	73	22	72		
90	22	76	22	75		

against load applied horizontally at the top. Unfortunately, pole classification has not yet reached a basis of national standardization. The old National Electric Light Association classification for Western Red cedar, Northern White cedar, and chestnut are given in Table XIV. These are used to a large extent at present but have been given considerable study of recent years and new classifications, reducing somewhat the top diameter requirements and adding more classes, has been proposed but not yet officially adopted. A great many companies buy their poles by top diameter only, the cost being usually somewhat less than that of "class" poles. As this gives no check on the butt diameter and, hence on the real strength, it is to be recommended that no matter on what basis poles are purchased, they be classified according to some fixed standard of strength before being set, and in distributing them for use, the strength be fitted to the service requirements. In general it will be found advisable to use a pole of at least the next higher class to that general for the line, wherever an extra stress is likely, as at dead ends, corners, guyed poles, transformers poles, etc.

Framing.—In preparing a pole for use, it is customary to shape the top. Two forms are ordinarily used, the gable roof



(a) Gable Roof (b) Cone Roof

FIG 178—Pole roof

and the cone roof as indicated on Fig. 178. The cone roof sometimes has a flat section at the peak. Convenience in cutting the roof is the criterion of choice, as neither has any particular advantage otherwise over the other. In fact there is probably no practical necessity for any roof.

For attaching cross-arms a flattened surface on the side of the pole is necessary, sufficient to give some rigidity to the construction. Ordinarily a space 3 to 4 in. across (on the flat) is all that is required, making a cut of about ¼ in. into the pole. These cuts, or "*gains*," are often cut square with a saw at top

and bottom to just fit the height of the cross-arm, Fig. 179(*a*). Comparatively little support is afforded to arm thereby, and a gain made with a draw shave is sometimes used, with economy, Fig. 179(*b*).

It is advisable when using yellow-pine poles which are treated full length that the roof, gains, and also all bolt holes be cut before the pole is treated, as otherwise they are points in which decay is likely to start.

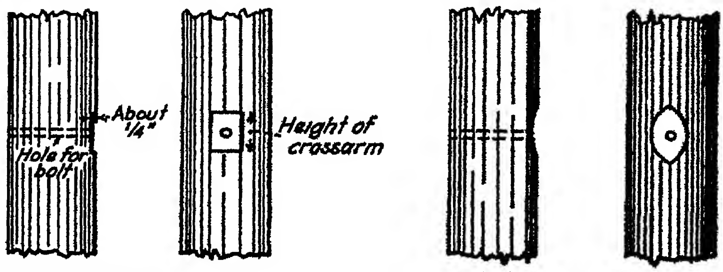


FIG. 179.—Pole gain.

Loading and Stresses.—A pole is essentially a column, subject to two kinds of stresses. The dead weight of the load carried imposes a direct compressive stress along the axis which may be considered as uniformly distributed over the cross-sectional area, and is transmitted into the ground underneath, Fig. 180 (*a*). In addition, the horizontal wind pressure on the pole and on the wires and other equipment supported constitutes a load applied to the pole as a cantilever beam, with its fixed end in the ground. This load sets up the usual bending stresses in the pole (tension on one side and compression on the other) and its overturning moment is opposed by earth pressure on the sides of the pole, Fig. 180 (*b*). The stresses of direct compression are added to those due to the bending stress to give the total stress. On the ordinary line pole, supporting wires only, the latter (in pounds per square inch) is usually so much smaller than the former that it is negligible. On transformer poles, on the other hand, it may become much more important and should not be forgotten in any case.

The loading to be assumed is given by the National Electrical Safety Code as:

> Vertical.—Weight of wires plus assumed ice covering (½ in. radial thickness for heavy loading, ¼ in. radial thickness for medium loading, no ice for light loading).

Horizontal.—Wind pressure on pole plus wind pressure on ice-covered wires (as above). Pressure assumed to be 8 lb per square foot of projected area for heavy and medium loading and 12 lb. per square foot for light loading

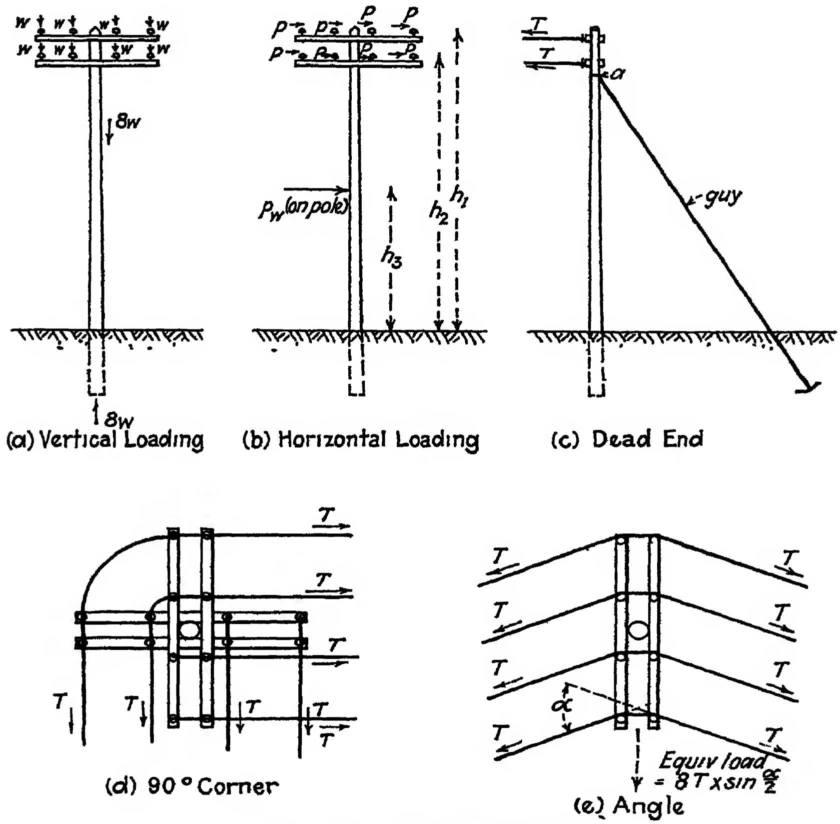


FIG 180 —Loading on poles

(Weight and wind pressure on any other equipment carried must, of course, be added where they are of any appreciable importance.) Data on wind loading on wires are given in Chap. XXII.

At dead ends, corners, and angles in the line, and also in case the wires become broken, the tension in the conductors becomes a loading on the pole, Fig. 180 (*c*) and (*d*). This tension is further discussed in Chap. XXII. As a rule the maximum is about 50 per cent of the ultimate strength of the conductor, for copper at least (60 per cent is allowed by the Safety Code for Grade *C* construction). If the tension actually tends to become much greater than 50 per cent, the wires will stretch appreciably,

increasing the sag and hence reducing the tension, since the practical elastic limit of copper is in the neighborhood of 50 per cent of its ultimate strength.

At a dead end, the full tension of all the wires must be supported. At any angle in the line, the load due to each wire is equal to the tension in that wire times twice the sine of one-half the angle made, $2T \sin \frac{\alpha}{2}$, see Fig. 180 (*e*). The resultant load is the sum of the loads of the individual wires.

Example.—Assume tension in wire = 500 lb.

Angle of line (α) = 20 deg.

$\sin \frac{\alpha}{2} = \sin 10 \text{ deg.} = 0.1736$

Resultant stress due to each wire
$= 2 \times 500 \times 0.1736 = 173.6$ lb.

If there are 4 conductors carried on the pole the total resultant stress is 694.4 lb.

As a rule at dead ends and angles (except very slight ones) the pole is either not strong enough or not stable enough to support the load unaided, and the customary practice is to install guys at such points. Where guys are used, the pole is assumed (according to the Safety Code) to act as a strut only, the guys taking all the horizontal stress. This will be further discussed in Chap. XXIV. Even with guys however, there is often a short section of pole above the point of attachment of the guys whose strength must be considered, Point (*a*), Fig. 180 (*c*).

Stress Computation.—Considering the pole as a column only, supporting the dead weight of its load, the stress may be assumed to be uniformly distributed over its cross-sectional area and the unit stress is

$$f = \frac{W}{A}, \tag{68}$$

where

f = unit compressive stress in pounds per square inch.
W = total weight supported in pounds.
A = cross-sectional area $= \frac{\pi d^2}{4}$ for circular cross-section.
d = diameter in inches, at the point considered.

If this stress is of any considerable importance, *i.e.*, anywhere near the allowable strength of the wood, the slenderness ratio

of the pole must be considered That is, the unit strength in compression which would otherwise be considered allowable must be reduced to allow for the ratio of the diameter to the unsupported length, the pole being a slender column. Such a condition does not usually occur however in this work. The reduction in allowable stress due to slenderness may be expressed as follows:[1]

$$f_1 = f\left(1 - \frac{L}{60D}\right)$$

where

f_1 = the allowable stress.
f = the allowable stress without allowance for slenderness.
L = unsupported length of column in inches.
D = diameter of column in inches.

Considering the pole as a cantilever beam under horizontal wind stresses (or load due to wire tensions, as at dead ends or corners or with broken wires), the maximum fiber stress at any cross-section is

$$f = M\frac{y}{I} \tag{69}$$

where

f = maximum unit stress in pounds per square inch.
M = bending moment of applied forces about the section chosen, in inch pounds.
y = distance from extreme fibers of cross-section to neutral axis.
I = moment of inertia of the cross-section.[2]

The maximum fiber stress in this case occurs at the extreme edges of the cross-section (farthest from the neutral axis), being compressive on the side toward which the load is acting and tensile on the opposite side.

In the case of a pole of circular cross-section the moment of inertia I is equal to

$$I = \frac{\pi d^4}{64} = 0.0491d^4. \quad y = \frac{d}{2}, \quad f = \frac{M}{0.0982d^3},$$

therefore,

$$\frac{I}{y} = \frac{\pi d^3}{32} = 0.0982d^3 \text{ (called the } \textit{section modulus}\text{)}.$$

[1] N E L A. "Overhead Systems Reference Book," p. 370.
[2] See Chap. XXX for further details regarding these quantities.

The *bending moment* is equal to the force applied times its distance in inches (at right angles to its direction) from the point whose strength is being considered, Fig. 180 (*b*). For wind pressure *on the wires* the effective distance is easily determined and

$$M = ph \text{ inch-pounds,}$$

where

p = the pressure in pounds on the length of wire (plus ice) supported.

h = its distance in inches above the cross-section being studied.

For several wires, the total moment equals the sum of the values of $p \times h$ for all the wires.

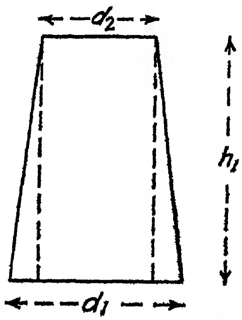


FIG. 181.—Diagrammatic representation of projected area of a pole.

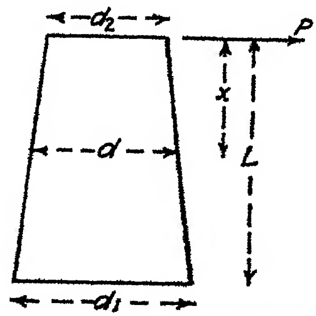


FIG. 182.—Determination of weak section of a pole.

For the wind pressure *on the pole* itself, the moment is not so easily computed. The projected area of the pole is in the shape indicated on Fig. 181. This may be resolved into a rectangle and a triangle.

The pressure on the rectangle $= p_1 d_2 h_1$, where

p = unit pressure in pounds per square inch.

$$\text{Its moment about the base } = p_1 d_2 \frac{h_1^2}{2}.$$

$$\text{The pressure on the triangle } = p_1(d_1 - d_2)\frac{h_1}{2}.$$

$$\text{Its moment about the base } = p_1(d_1 - d_2)\frac{h_1^2}{6}.$$

$$\text{Total pressure } = p_1 h_1 \frac{(d_1 + d_2)}{2}. \qquad (70)$$

Total moment (due to wind on pole) $= p_1 h_1^2\left(\frac{d_2}{2} + \frac{d_1}{6} - \frac{d_2}{6}\right)$

$$= p_1 h_1^2\left(\frac{d_2}{3} + \frac{d_1}{6}\right) \text{ inch-pounds.} \qquad (71)$$

Theoretically, the weakest section of a pole of uniform taper and uniform unit strength is where the diameter is one and one half times the diameter at the point where the resultant load is applied (resultant load being total load applied at $h_t = \frac{\text{Total moment}}{\text{Total load}}$, above the ground). This may be proved as follows·

In Fig 182, let P = total applied load applied where diameter $= d_2$.

d = diameter at weak section at distance x from P

t = taper of pole $= \frac{d_1 - d_2}{L}$.

Bending stress at weak section,

$$f_d = \frac{Px}{0.0982(d_2 + tx)^3}.$$

For a maximum value of fd, set first derivative $\frac{df}{dx} = 0$,

$$\frac{df}{dx} = d_2 + tx - 3tx = d_2 - 2tx = 0$$

$$d_2 = 2tx = 2(d - d_2).$$

$$d = \tfrac{3}{2}d_2.$$

The stress at that point is obtained as follows:

$$f_d = \frac{Px}{0.0982d^3} = \frac{Px}{0.0982\left(\frac{3}{2}\,d_2\right)^3}.$$

$$x = \frac{d - d_2}{d_1 - d_2}L = \frac{d_2}{2(d_1 - d_2)}L.$$

Substituting,

$$f_d = \frac{PLd_2}{0.0982\left(\frac{3}{2}d_2\right)^3 \times 2(d_1 - d_2)} = \frac{PL}{0.662(d_1 - d_2)d_2^2} \qquad (72)$$

which is in terms of diameter at point of application of resultant load, diameter at base, and total moment at base.

The above holds true only when the weak section is above the ground line. Otherwise the weak section is at the ground line and the stress is

$$f_d = \frac{PL}{0.0982 d_1^3} = \frac{M_t}{0.0982 d^3}. \qquad (73)$$

Where M_t = the total moment at the ground line, and is equal to the sum of the moments of the wind loads on all wires and on the pole itself computed as shown above, plus any other wind loads on equipment, etc., which may be present.

For most practical purposes computations made with the assumption that ground line is the weakest section will not be greatly in error. They are sufficiently accurate at least for general line design where only average figures on pole dimensions are used. This is especially true where the ground line is somewhat affected by decay and hence reduced in diameter. The fallacy of attempting to use too great exactness in such computations is shown by experience with poles broken in practice and in test. The taper is rarely exactly uniform, and the wood is probably never of uniform strength. Also, defects such as knots, butt rot, crookedness, non-circular cross-section, etc. are the rule, rather than the exception and heart rot is not uncommon. It is observed that poles may break at almost any point between the ground line and the top. The break occurs usually with a considerable amount of splintering, or separation of the fibers and rarely square across. Sometimes the break takes place as a shearing for most of the length of the pole. The computation of strength on the above given basis, using the ground line as the weak point, will be found the best guide obtainable at present as to probable strength of poles on the average.

Example of Computation for Pole Strength.—Assume 40-ft. pole, set 6 ft. in ground.

3 No. 4 T.B.W.P. wires on top arm, wires level with top of pole.

3 No. 4 T.B.W.P. wires on second arm, 2 ft. below top arm.

Span 125 ft., heavy loading assumed.

Pole 8 in. in diameter at top, 12 in. in diameter at ground line.

Moment due to wind on ice-covered wires,

$3 \times 125 \times 0.906 \times 34 = 340 \times 34 = 11{,}560$

$3 \times 125 \times 1.000 \times 32 = 375 \times 32 = \underline{12{,}000}$

23,560 ft.-lb. = 282,720 in.-lb.

Moment due to wind on pole,

$$M_p = \frac{9}{144} \times (34 \times 12)^2 \left(\frac{8}{6} + \frac{12}{3}\right) = 80{,}150 \text{ in.-lb.}$$

Total moment at ground line, 362,870 in.-lb.

$$f = \frac{362,870}{0.0982 \times 12^3} = 2,140 \text{ lb per square inch.}$$

If the pole is Western Red cedar with an ultimate strength of 5,000 lb. per square inch, the safety factor under this load is 2.33

Where the loading is due to tension in wires rather than wind loading, the same principles of obtaining moments as given above should be followed, using wire tensions rather than wind pressures for the loads due to the wires. Where the maximum wire tension used is based on a maximum wind and ice loading it is sometimes questionable as to just what combination of loads should be used. For example, with a very slight angle, the loads due to wire tension should be added to those due to horizontal wind pressure on both pole and wires for the worst possible condition. At a 90-deg. angle however, maximum wind pressure on wires in both directions cannot be possible. Considerable good judgment can be exercised in determining just what combination of loads should be assumed for the worst probable condition for which to design the structure.

Safety Factors.—When the probable worst stresses in the pole have been determined, the size must be selected on the basis of known unit strength of the timber, with usually some factor of safety applied to care for unknown or unforseen conditions which may create greater stresses than those computed. The ultimate strengths of various kinds of pole timber are given in Table XIII. Safety factors as required by the Safety Code are shown on page 290.

Where this Safety Code, or its equivalent in local rules, is not in effect, to specify definite safety factors which must be applied under various conditions, the engineer must use his own judgment in selecting such safety factors as will best meet his own conditions, taking into account probable unforeseen or unusual loadings, requirements for continuity of service, hazards to life and property, probable depreciation of poles, etc. The safety factors given in the Safety Code are probably large enough for all ordinary purposes and in certain cases could no doubt be diminished somewhat without undue danger. In general, a safety factor of about 2 when installed and 0.67 to 1 when replaced is conservative for ordinary conditions where special strength is not required.

TABLE XV.—SAFETY FACTORS FOR POLES[1]

	When installed		At replacement, treated or untreated poles
	Treated poles	Untreated poles	
At crossings			
Pole lines of one grade of construction throughout:			
Grade A	3	3	2
Grade B	2	2	1.33
Grade C	1.33	1.33	.67
Poles in isolated sections of higher grade of construction in lines of a lower grade:			
Grade A	3	4	2
Grade B	2	3	1.33
Grade C	1.33	1.67	.67
Elsewhere than at crossings:			
Grade A	2.5	3	1.67
Grade B	1.67	2	1
Grade C	1	1.33	.67

[1] National Electrical Safety Code.

Grades of Construction.—In Table XV, grades of construction A, B, and C were mentioned. These are Safety Code classifications of line construction which apply to different conditions, more or less according to the assumed hazard involved. In general they may be defined as follows:

Grade A.—All supply circuits, where crossing over main tracks of railroads.

Open-wire supply circuits of over 7,500 volts or constant-current circuits exceeding 10 amp., where crossing over or in conflict with major communication circuits.

Grade B.—Open-wire supply circuits of over 7,500 volts in urban districts under nearly all conditions except as noted above under Grade A.

All supply circuits, where crossing over minor tracks of railroads.

Open-wire supply circuits of over 7,500 volts or constant-current circuits exceeding 10 amp. where crossing over or in conflict with minor communication circuits.

Open-wire supply circuits of 5,000 to 7,500 volts or constant-circuit currents of 7.5 to 10 amp., when crossing over or in conflict with major communication circuits.

Grade C.—Open-wire supply circuits of over 7,500 volts in rural district where crossing over or in conflict with supply circuits of 0 to 750 volts (excepting services).

Open-wire supply circuits of 750 to 7,500 volts in urban districts under nearly all conditions except as noted above under Grades A and B; also where crossing over or in conflict with major or minor communication circuits

NOTE.—*Conflict* between structures carrying supply and communication circuits as used above is defined as a situation where the overturning of one line (at the ground line) will result in contact between its poles and conductors and those of the other line Lines are not considered as conflicting where crossing each other or where on opposite sides of a highway, street, or alley if separated by not less than 60 per cent of the height of the taller pole and not less than 20 ft. For the purposes being considered the same rules apply to lines on the same poles as to lines which conflict.

For most of other conditions, no particular grade of construction is required, only the general rules concerning clearances, etc., being applied. There are, however, in the Safety Code a very large number of exceptions and complications of the general rules, which have been only roughly summarized above, such as provision for cabled supply lines, communication circuits used in the operation of supply circuits, etc. Reference should be made to the National Electrical Safe Code for complete information on the Grade requirements.

Stability.—In the above discussion of pole strength, it has been assumed that the pole is held rigidly in the ground. This may be the case under certain conditions such as settings in rock or in soil which is solidly frozen. Since sleet storms in heavy-loading districts are likely to occur in the winter when the ground is frozen, the assumption is probably justified for those districts, as a worst condition. Under ordinary conditions of unfrozen soil, however, even if firmly packed, the setting is usually by no means rigid. The rididity of course depends considerably on the factors of depth of setting, character of soil, firmness of packing of soil, and special means employed, such as heel-and-breast blocks of concrete, to stiffen the setting, and also on the relative strength and stiffness of the pole itself. It is comparatively difficult, however, to set a sound pole of strength of Class C or greater, even with a reasonable amount of special blocking,

in such a way that it will not be pulled a considerable distance out of the vertical before it is broken. The flexibility of the pole itself is also usually ignored, yet this allows the pole top to be pulled a comparatively long way out of line without breaking, even in rigid settings. These facts have a practical value, in that in a great many situations, the pole may be depended upon to "give" somewhat and thus relieve the stress before it breaks and lets the line down. In districts where frozen ground is not a factor, it may be possible thereby to reduce the safety factors used.

Some results of tests made on poles set forth in clay and in sand are shown in Table XVI. Various forms of supplementary blocking was used, *i.e.*, concrete full depth of hole, concrete top and bottom with earth between, crushed stone tamped in

TABLE XVI.—TEST ON POLE SETTINGS

Type of setting	Circumference of pole at ground line, inches	Maximum pull applied, pounds	Deflection at top, inches	Deflection at ground line, inches	Deflection after load was removed	
					At top, inches	At ground line, inches
Hard yellow clay soil:						
Concrete, full . .	30	2,500	18⅞	1¼		
		3,000	35⅞	1⅛	8	1½
Concrete, top and bottom	40½	2,500	22	½		
		2,900	27	¾	0	¾
Crushed stone, top and bottom	40	2,500	47⅜	4	13⅝	2¼
Same.	40	2,200	33⅞	2½		
		2,700	45⅝	3⅛	12⅝	2¼
						pole cracked
Log at top, stone at bottom . .	40	2,500	44⅝	3	9⅝	2
Same	41½	2,500	50⅛	3⅛	20	2¾
Cobble stones. . .	39½	2,500	42⅛	2¾	7⅝	1⅝
Same	39	2,500	32⅞	1½	8	¾
Plain earth.	38	1,400	44⅝	4¾	30½	4¼
Soft yellow sand:						
Concrete, full .	40	2,500	16⅝	1		
		2,900	19¾	1¼	5	1
Concrete, top and bottom	33	2,500	22⅛	1⅜		
		2,900	39⅛	1¾	6¾	1
Crushed stone, top and bottom	43	2,900	48⅛	4⅝	16⅝	3¼
Same.	39	2,350	43⅞	4	18½	3⅛
9-in. log at top, stone at bottom	40	1,800	45⅞	3⅝	21⅞	2½
Same.	37	2,350	57¾	5⅛	31¾	4¾
Cobble stones top and bottom	40	2,500	77⅛	5¾	25⅞	5⅛
						pole cracked
Same.	38	2,500	45⅛	2¾	17¾	2⅛
Cobble stones and fresh concrete top and bottom.	39	2,500	52	6	25¾	4¾
Plain earth	46	2,000	33	4½	25¼	3

hole full depth and also top and bottom only, and cobble stones tamped in hole. The results, while not at all uniform due to variations in the size of pole and other conditions, are yet indicative of the relative stability of the settings. The soil was somewhat wet in both cases due to recent rains.

Stress was applied in each case 25 ft. above ground.

Poles all set 6 ft. deep.

In only two cases did the pole break in the test, and these were only cracks, not complete failures.

In some cases the pole was raked, but this did not seem to have any consistent effect in decreasing the movement under load.

A theoretical computation of pole stability can be made based on assumed homogeneous soil condition with uniform resistance to pressure. The method is indicated in Fig. 184. It is felt however that, with the multitude of variable factors encountered, such a computation is not often of any considerable practical value, hence it will not be dwelt upon further.

Setting.—The depth of setting of poles has considerable bearing on their stability. It has been shown by test that in general from 4½ to 5 ft. depth in soil is essential for any pole to allow it to develop anywhere near its full strength.

The depth of setting recommended by the Safety Code are given in Table XVII

Table XVII.—Depth of Setting for Poles

	In soil	In rock
20	5 0	3 0
25	5 5	3 5
35	6 0	4 0
40	6 0	4 0
45	6 5	4 5
50	7 0	4 5
55	7 0	5.0
60	7 5	5 0
65	8.0	6.0
70	8.0	6.0
75	8 5	6.0
80	9 0	6.5

As a rule somewhat deeper setting should be used for poles which are under extra heavy stress as at corners, etc., than for poles in the straight line.

Where soft-soil conditions are encountered or where proper guying is impossible or undesirable, supplementary blocking of some sort must be resorted to in order to increase the stability

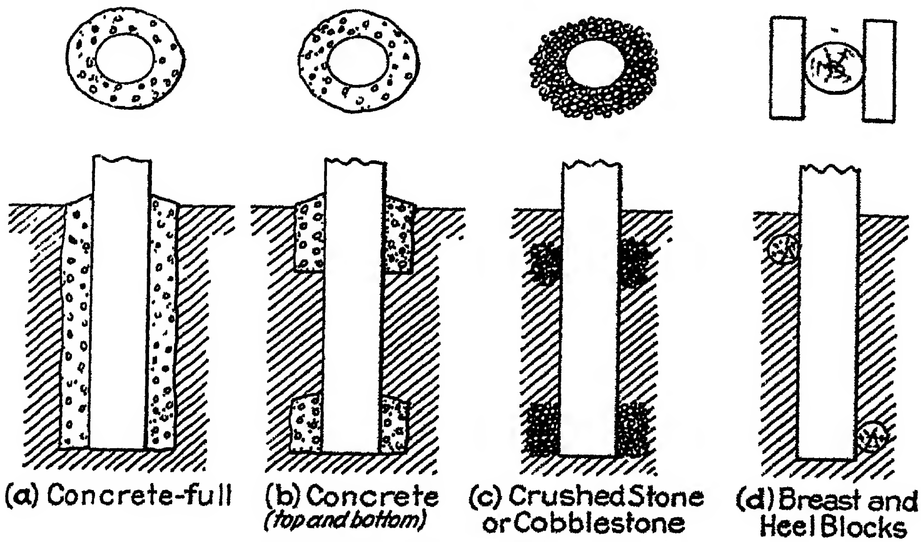


FIG. 183.—Reinforced pole settings.

of the setting. Several forms of such reinforcement were mentioned above in connection with the stability test quoted. Sketches of these are shown on Fig. 183. The theory on which

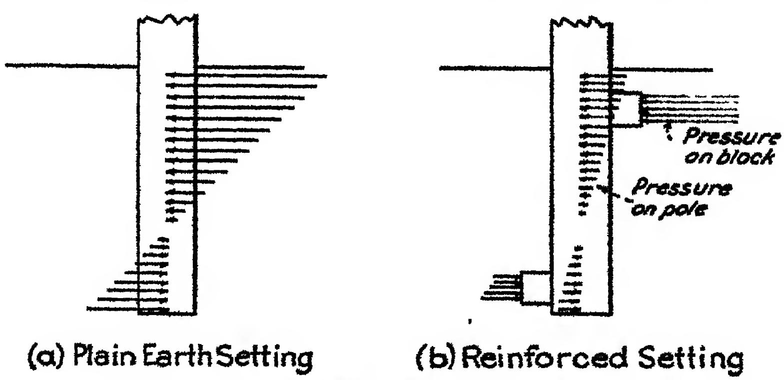


FIG. 184.—Pressures on earth for pole settings.

such settings are based is that the area of pressure against the earth must be increased sufficiently so that the unit pressure is reduced to an amount which can be supported. Figure 184 indi-

cates the difference in the theoretical earth pressure distribution with plain setting and with reinforced setting. In the former, the pressure is distributed over the whole depth, decreasing from a maximum at the top to 0 at ⅔ depth and increasing again to a maximum in the opposite direction at the bottom. The reinforcing concentrates the stress largely on itself. Of course such settings as solid concrete have similar pressure distribution on the outside of the concrete as on the pole in plain earth, and crushed stone or cobble stones have some intermediate effect.

Guying.—The most efficient method of supplementing pole strength and stability where comparatively large stresses are to be met (beyond the ordinary strength of the pole or its setting) is, ordinarily, by use of guys to other poles or to ground anchors. In such cases, the pole is usually figured as acting only as a strut, the guys taking all the horizontal load. Guying will be taken up more fully in Chap. XXIV so will not be dwelt on here.

Maintenance.—Proper maintenance of pole lines is fully as important as proper original design. It is in the nature of such a structure, which is constructed of more or less perishable materials and located in a more or less yielding foundation, that it deteriorates with age. The deterioration in this case takes the form of decay at the ground line, decay above the ground line, decay in the interior of the pole, damage due to insects (and in some cases due to birds such as woodpeckers), and in the displacement of the pole from its original position.

The latter change is one which is usually due either to unforeseen or unusually heavy loading (wind storms, etc), unexpected yielding of the setting, or in faulty design. It is easily discernible and comparatively easy to correct. Such displacements are often ignored unless of extreme amounts but this is likely to be short-sighted economy. Displacements of poles are likely to lead to more serious troubles due to the attendant displacement of conductors. Also, the effect of poorly maintained lines on public opinion and public relations is difficult to estimate. Well-constructed and well-maintained pole leads are good advertisements and good assets.

Deterioration of poles due to decay or to insects has been discussed under pole treatment. Proper treatment can prevent a great deal of such trouble and delay final deterioration considerably. External decay at the ground line is comparatively easy to detect and definite rules can be established as to the reduction

in diameter which can be allowed before the pole becomes sufficiently weakened to require replacement. In Table XIV the requirements of the Safety Code in this regard are stated in the form of safety factors required for various conditions. In general, a reduction of from 33 to 50 per cent in the safety factor at the time the pole is new is allowed before replacement is required. It might possibly appear that the reduction in strength in some of these cases would be inadvisable from the standpoint of safety. It must be remembered however, that poles in a line do not depreciate uniformly. Certain poles decay more rapidly than others, and, if the worst poles are kept above the minimum safety factors given, the best poles will in most cases be much stronger, and the average for the line is considerably above the minimum. The diameters of poles necessary to meet these safety factors can be easily computed from the formulæ given above, if the maximum loading is known.

Internal decay or heart rot, while not of as frequent occurrence as ground-line decay if sound poles are set originally, is, however, possibly more serious, in that it is much more difficult to detect. A hollow pole may appear perfectly sound on the exterior, except perhaps at some of the knots. The extent of such decay or the remaining strength of the poles is very difficult to estimate unless borings are made into the pole.

Some companies use quite complete records of pole installation and make periodic inspection of each pole after it has passed a certain age, such as 10 years, to determine when replacement should be made. One company makes a practice of requiring test borings to be made in any pole before it is climbed, when it is beyond a certain age or has not been previously tested within 2 years. Others make periodic or intermittent inspections of the whole system, recording at such times the probable future life of any leads which are still within minimum requirements but which will probably need replacement shortly. The extent to which such routines and records are applied is largely an economic question, due regard being given to hazard to life and property. Broken poles in service are likely to be expensive but, on the other hand, complicated records are also expensive and may go beyond the practical requirements for satisfactory maintenance. Some form of regular inspection is no doubt justifiable.

Location.—The proper location of poles in a lead is a matter which requires a considerable amount of experience and knowl-

edge of the practical considerations affecting line construction. Local regulations and practices are involved to quite an extent and general rules are, for the most part, not possible. A few principles may be stated which are quite generally applicable.

1. Definite location for each pole should be decided upon ahead of actual construction (usually staking out locations is advisable). The layout may be thus made by an engineer who can give due consideration to all the factors involved, such as local regulations, strength of construction, clearances over obstructions, future needs, right of way, tree trimming, etc., and make special study of unusual conditions. Time of the construction crew is thus conserved, numerous possible delays being avoided.

2. Pole leads of one utility should occupy the same side of a highway for its whole length or at least considerable portions of it. It is a quite generally recognized principle (definite rule in some States) that on any highway, one side should be reserved for supply circuits and the other side for communication circuits, unless both occupy the same poles. The practice of jumping back and forth across a highway to avoid trees is not only unsightly but is also likely to necessitate rebuilding of the lead at some time in the future. There are, of course, exceptions to the rule, such as where extremely large trees are encountered and joint construction for both facilities on the opposite side of the road is practicable.

3. Where the property traversed is subdivided into lots, location of poles on or near lot lines (or opposite them in streets or alleys) is usually preferable. More services can ordinarily be reached with greater ease from a lot line location, and interference with driveways, garages, etc., is less likely.

4. Future requirements in the way of additional wires (requiring higher or stronger poles or shorter spans) and possible branches or intersecting lines (requiring poles at the intersection points) should be foreseen as far as possible.

5. Future changes in topographical conditions such as pavement of streets, sidewalks, regrading, etc., should be anticipated, pole locations being chosen where they can be permanent as far as possible.

6. In passing a tree which is likely to interfere with the line, a pole should be set as near the tree as practicable to minimize the trouble from swinging wires.

7. Where there is any choice, locations should be selected which are least subject to damage from traffic.

8. Pole leads should be in straight lines wherever practicable.

9. Consideration must be given to provisions for properly guying the lead and pole locations chosen accordingly.

10. Spacing between poles must be such that the pole will not be loaded beyond its strength.

Spacing.—The spacing of poles, or span length which should be used, depends considerably on the locality in which the line is situated. Under any conditions the essential requirement is, of course, that the spans be short enough so that the strength of the poles is not exceeded (with proper safety factor) under the worst assumed loading. That is, the allowable length of span for any given number and size of conductors is proportional to the strength of the pole to be used. There are other limiting considerations however.

In urban districts the number of wires and the wire sizes are likely to be comparatively large. There is also somewhat greater necessity, as a rule, for providing for future additional circuits than is the case in rural or suburban territory. The grade of construction required by the Safety Code is higher for urban territory. In addition to these factors, there is usually the requirement that the poles be located in accordance with lot lines and where services can be conveniently run to customers. A few typical layouts are shown in Fig. 185. As a general rule, span lengths in urban districts do not usually average much over about 125 ft. with maximum of about 150 ft. In some cities, especially where joint use with communication circuits is a rule, the span length is limited to about 100 ft.

In suburban territory much the same limitations are imposed as in the cities, except that lots are likely to be somewhat wider and loading somewhat lighter. Average span lengths may be increased correspondingly.

In rural territory a different condition exists. Span lengths are seldom limited by property lines or by the necessity for reaching more than one service from the same pole. As long spans can be used as are consistent with economy and with wire strength. The latter often becomes the limiting factor. Conductor sags are very nearly proportional to the square of the span, hence increasing the span length materially will necessitate increasing the conductor sag. There is a practical limit for any conductor

when clearances above-ground and spacing between wires are taken into account. In heavy-loading districts, spans of 175 ft. are about the limit for No. 6 copper with a reasonable sag

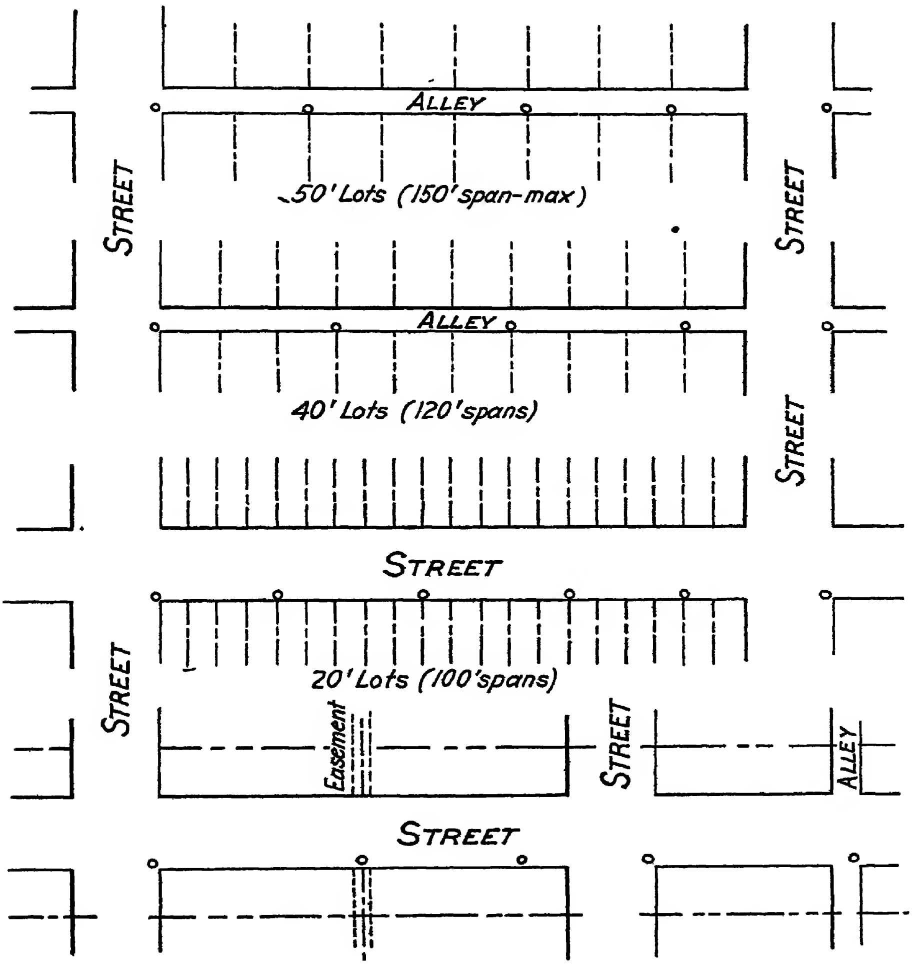


FIG 185 —Typical pole layouts in streets, alleys, etc

With No. 4, 200 ft. is about a maximum. If higher strength conductor is used, however, the smaller sags required may allow longer spans. The maximum span which is generally used, even in this case, is about 300 ft. A type of line which has been found practical and economical for rural lines, where only two or possi-

bly three conductors will be carried, uses No. 4 or No. 2 steel-cored aluminum conductor with 35-ft. poles in 300-ft. spans. In some localities 30-foot poles can be used, but where Safety-code provisions prevail, with frequent road crossings, 35-ft. poles are likely to be more convenient for the whole line. If secondaries are needed for short distances or if more wires are added in the future, intermediate poles can be set making a line of 150-ft. spans.

Steel Poles and Concrete Poles.—The use of poles made of more durable material than wood, such as steel or reinforced concrete, has not become at all general in this country as yet. There is no doubt that such poles would give a longer life than the wooden pole ordinarily used and hence would appear to be economical. The first cost of such poles is much greater, however, than that of wooden poles of equal strength. In addition, they are considerably heavier and hence harder to handle and to set, and particularly harder to move or replace. In most places, the permanence of location or of size necessary for any pole are matters of considerable doubt. Streets and highways are being widened, streets are being paved, districts are being rebuilt with buildings of different character, congestion of population and of traffic are forcing lines underground, loads are increasing, requiring more and heavier circuits—all these elements combine to require frequent moving, replacement, or removal of many poles. It is possible that some day conditions may become so stabilized that it may be practicable to figure economy over a longer term of years than at present seems necessary. In such a case, concrete and steel poles will make a strong bid for consideration. The time may come also when such poles are cheaper in price than wooden ones. At present, however, their field is mostly for locations where good appearance is of especial importance—for they unquestionably have the advantage over wooden ones in that regard—where usually heavy loads are to be carried for which wooden poles are not adequate, or where conditions are such that wooden poles have an unduly short life.

Several types of concrete poles are manufactured, usually either of round or square cross-section, and either solid or hollow. The latter are formed by spinning the form after the concrete is poured, forcing it to the outside and leaving the center hollow. The strength of concrete poles lies largely in the steel reinforcement and depends also considerably on the mixture of cement and

how it is cured. The manufacturers of such poles classify them according to strength as follows:

Class	Safe Horizontal Load 2 Ft. from Top
A	4,000
B	3,000
C	2,000
D	1,500
E.	1,000

Steel poles are made either tubular or in some fabricated type, usually of the general form of two channels, angles, or tees, tied together with some sort of lacing. They are sometimes made of expanded metal, sometimes welded, sometimes bolted or riveted, the details and cross-section in each case being somewhat different. Space does not permit going into much detail here regarding steel poles in view of their limited use on distribution lines.

CHAPTER XVII

CROSS-ARMS

Wood cross-arms are the most commonly used medium for supporting distribution conductors carried on poles, especially primary circuits. The use of metal racks for secondaries has become a quite common practice of recent years and these will be discussed in Chap. XVIII. Metal brackets are used to some extent for primary wires and will be given some attention in Chap. XIX. Wood cross-arms, however, have by far the greatest general use for this purpose.

Materials.—One of the most satisfactory materials for wood cross-arms is Douglas fir. It has the necessary qualifications, being comparatively strong, tough, fairly light, easy to work, and yet is very durable. Another advantage is that it is available in large quantities and hence at a comparatively reasonable price. The better cross-arms usually contain at least 75 per cent of heartwood, the timber being cut from large trees. This no doubt is one reason for its durability. As a rule, no preservative treatment is considered necessary, the arms ordinarily having a life of 12 to 15 years or more without it. The ultimate fiber stress of Douglas fir is given as about 5,000 lb. per square inch in bending, and its weight 31.8 lb. per cubic foot. In some specifications, the number of annular rings per inch are limited to more than a certain minimum, such as 10. Some tests on a large number of samples with various numbers of rings per inch, from 6 to 40, indicated that there was little justification for this from the standpoint of strength, the examples with the fewer rings showing the highest strength in this case. The strength is likely to be more or less in proportion to the density of the wood, which is affected by the dark-colored or summer wood in the piece.

Another wood which has considerable use for cross-arms is southern yellow pine. This timber was discussed somewhat under "Poles" in Chap. XVI. Its strength is comparable to that of Douglas fir. It is usually treated with creosote before being used although it is sometimes claimed that, if made largely

of heartwood, its durability is high, being greatly different from that of the pole timber, which has a deep layer of sapwood on the exterior. When treated, pine cross-arms are of course considerably heavier than fir.

Sizes and Designs.—Wood cross-arms for electrical distribution work are generally of rectangular cross-section (or approximately so, being usually "roofed" slightly on top) of dimensions 3¼ by 4¼ in., 3½ by 4½ in., or 3¾ by 4¾ in., with the former two in the majority. The 3½ by 4½-in. size is adaptable to a wide range of service up to quite heavy conductors and is the so-called National Electric Light Association standard, being proposed several years ago as a suggested standard for low-voltage arms by the Overhead Systems Committee of the National Electric Light Association. The 3¼ by 4¼ in. has about as many advocates, especially where heavy conductors are not much used and, since its price is generally somewhat less due to its smaller dimensions, it also takes practically the status of a standard. The 3¾ by 4¾ in. is more used for the heavier loadings and sometimes for the higher voltages—the National Electric Light Association suggested standards for medium voltage arms use this size. Some companies use the lighter arm (3¼ by 4¼ in.) for light lines and the 3¾ by 4¾ in. for heavy. The choice must depend on local conditions as to loading and conductor size, experience, cost, etc.

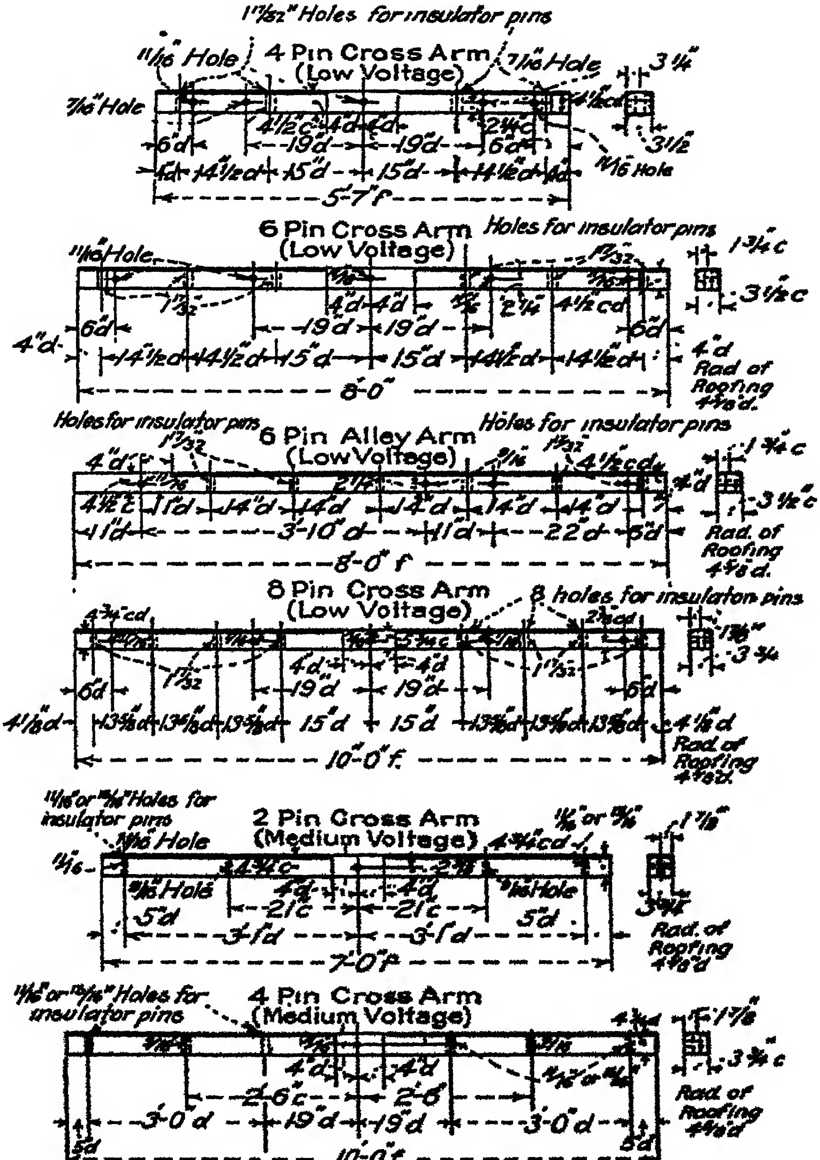
Lengths of arms are graded so as to accomodate 2, 4, 6, or 8 conductors as a rule, with spacings between conductors ordinarily approximately 14 in., except at the pole. The "climbing space" required by the Safety Code has regulated the spacing between pole pins on standard arms to 30 in. for voltages up to 7,500 volts, 36 in. for voltages from 7,500 to 15,000 volts, and sometimes more for voltages above 15,000.

Figure 186 shows the various National Electric Light Association suggested standard designs [1] While these are not universally used in exactly the details shown, they are representative of standard practice.

Uses.—The various ways in which cross-arms are customarily used are as follows:

Line Arms.—Cross-arms at right angles to the direction of the line, supporting the main conductors of the circuits (see Fig. 187 (*a*)).

[1] "Overhead Systems Reference Book," p 506, etc.



Allowable Variations		
	Over	Under
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"
cd	1/16"	1/8"

Fig. 186.—Crossarms (N.E.L.A. suggested standards).

Side Arms.—Arms, the greater part of whose length is on one side of the pole, used where clearances are limited, as in passing trees or buildings adjacent to the line or where the pole is somewhat out of the line of the main lead, to bring the conductors into

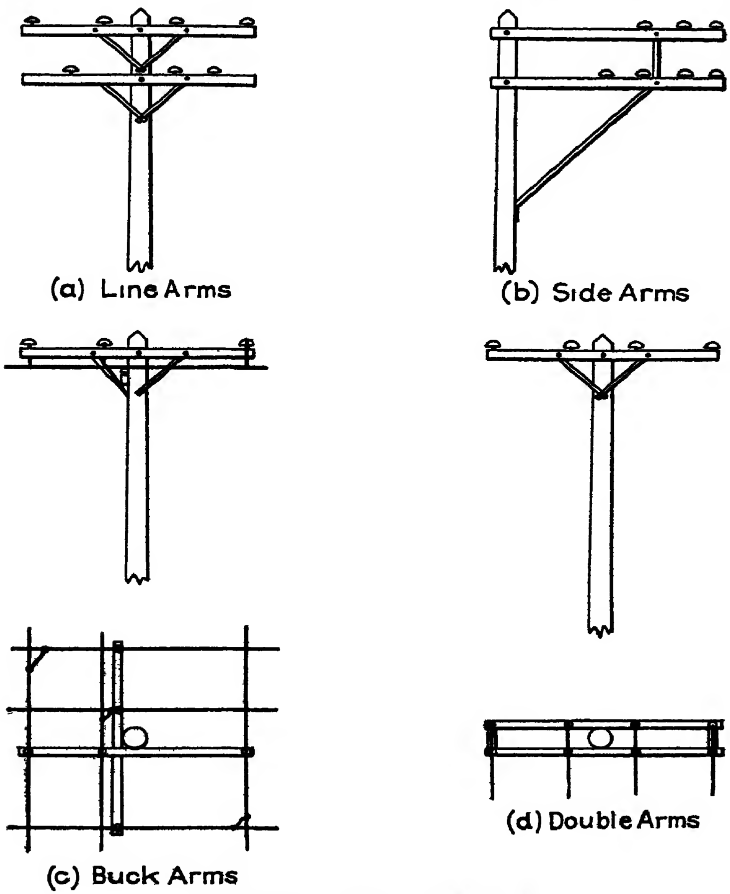


Fig. 187.—Use of crossarms.

line, see Fig. 187 (*b*). (The term "cross-arm" as distinguished from "side arm" is generally applied to cross-arms which are attached at their midpoint to the pole as in Fig. 187 (*a*).)

Buck Arms.—Cross-arms at an angle to the line arms (usually 90 deg.,) used for supporting service drops, branches, or intersecting lines, see Fig. 187 (*c*).

Double Arms.—Two cross-arms on the same level, one on each side of the pole, used at dead ends, angles, corners, and for

supporting unusually heavy loads, and in general wherever one arm alone will not have sufficient strength, see Fig. 187 (*d*).

Cross arms are also used for supporting transformers, for intermediate supports for training wires carried down the pole from the main circuit to transformers, cable entrances, etc., and other miscellaneous uses.

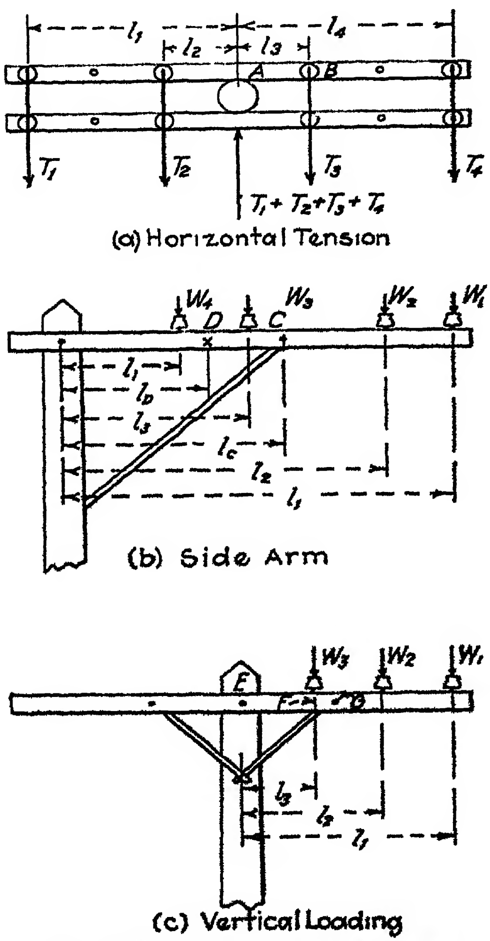


Fig. 188.—Loading on crossarms.

Loading.—The loads applied to cross-arms are those of the dead weight of wires with their ice loading, acting vertically downward, the weight of linemen standing on the arm when working on the line, and the horizontal stress due to tension in the wires at dead ends, under broken wire-conditions or any other cases where the tensions in both directions from the arm are not equally balanced. The magnitude of the wire loads are given in Chap. XXII, the dead load for any wire being ordinarily assumed as that due to the average of the spans on either side of the pole. The weight of the lineman may generally be taken at about 180 lb. average, applied at possibly two-thirds the distance from the pole to the end of the arm, although the Safety Code specifies 225 lb. at the extremity, for Grade A, B, or C construction. This weight should be added to that of the wires under the worst assumed conditions, since linemen are likely to be working on the poles under those conditions. Maximum tension in the wires may be computed from the loading and sags used, the practical limit being the elastic limit of the conductors (about one-half the ultimate strength, for copper) since beyond

that tension, the conductors would stretch materially and the stress would usually be relieved.

The cross-arm acts under both types of loading essentially as a beam, supported at the point of attachment to the pole and, under vertical loading also supported at the point of attachment of the braces, see Fig. 188. Under horizontal stresses, the braces cannot be considered to furnish any support, the arm acting as a simple beam supported at the middle. With side arms under vertical loading the brace must be assumed to give a virtually rigid support since that is essential to the design. With symmetrically placed *cross-arms* however, it is somewhat problematical as to just how much support is given by the brace, especially if the ordinary flat braces are used. For arms loaded on one side of the pole only, it is sometimes assumed that the brace on that side is inoperative, since it has little strength in compression, all the support coming from the brace on the opposite side of the pole, in tension. The loaded side of the cross-arm then would act virtually as a cantilever beam, supported at the pole. This assumption is probably seldom correct, especially if the braces are installed without being bent much. Although the flat brace has little rigidity under compression loading, tests indicate that the whole structure is considerably distorted from its original position before appreciable buckling is noticeable in that brace. On the other hand, it probably does not give anything like a rigid support, hence its exact action is questionable. As a rule cross-arms under vertical loading are comparatively strong when other factors of the design are satisfied, and it will be found sufficiently accurate to compute their strength on the basis of no support from the brace which is in compression. With more rigid braces, such as the one-piece angle iron brace which is discussed later, the brace on the load side may be assumed to give a practically rigid support as far as computing cross-arms strength is concerned.

Stress Computations.—Since the cross-arm is essentially a beam, the ordinary formulae for computing stresses in beams may be applied, *i.e.*,

$$f = \frac{M}{I/y}, \tag{74}$$

where

f = maximum unit fiber stress in pounds per square inch, occurring at the extreme edges of the cross-section

under consideration, being compressive on one side and tensile on the opposite side.

M = total bending movement in inch-pounds about the section under consideration.

I = moment of inertia of the cross-section.

y = distance in inches from neutral axis of cross-section to extreme edge.

The total bending moment M is equal to the sum of all the individual loads times their distances from the cross-section being considered. Just what point of the arm should be assumed as the weakest may be open to some doubt, especially where wood pins are used and a large pine hole is cut in the arm. For the symmetrically placed arm for example, Figs. 188(a) and 188 (c), the weakest section may be at the middle of the arm or it may be at one of the pin holes. The net cross-sectional area is less at the pin holes but the moment at the center is greater. The weakest point can be determined theoretically by computing f at both points, using the formula given above.

Another practical factor enters into the consideration of Fig. 188 (a), that is the support given the arm by the pole gain. Tests have shown that for the ordinary six-pin, 8-ft. cross-arm, the weak point under horizontal stress is more likely to be at the first pin hole from the pole than at the middle of the arm.

Examples of computation of moments may be taken from Fig. 188 as follows:

Figure 188(a), moment about A (middle of arm) $= T_1l_1 + T_2l_2$ or

$$= T_3l_3 + T_4l_4$$

Figure 188 (b), moment about B (first pin hole) $= T_4(l_4 - l_3)$.

moment about C (brace) $= W_1(l_1 - l_c) + W_2(l_2 - l_c)$.

moment about D (intermediate point) =

$$W_1(l_1 - l_d) + W_2(l_2 - l_d) + W_3(l_3 - l_d) - P_c(l_c - l_d),$$

where

$$P_c \text{ (reaction at brace)} = \frac{W_1l_1 + W_2l_2 + W_3l_3 + W_4l_4}{l_c}.$$

Figure 188(c), moment about F (first pin hole) =

$$W_1(l_1 - l_3 + W_2(l_2 - l_3)\text{—approximately},$$

neglecting small negative moment due to reaction of brace at G.

Moment about E (middle of arm) or any other point between G and E depends on the rigidity of the support given by the brace at G, and may be computed for any given assumptions by the continuous beam method shown in Chap. XXX.

The value of I, the moment of inertia, for a rectangular cross-section is equal to $\frac{1}{12}bd^3$, and $y = d/2$, hence,

$$\frac{I}{y} = \frac{1}{6}bd^2, \qquad \text{see Fig. 189}(a).$$

If the neutral axis is parallel to d, $I/y = \frac{1}{6}db^2$.

Where a pin hole or bolt hole with its axis at 90 deg. to the neutral axis is removed from the section, Fig. 189(b),

$$I = \tfrac{1}{12}(b - a)d^3,$$

and

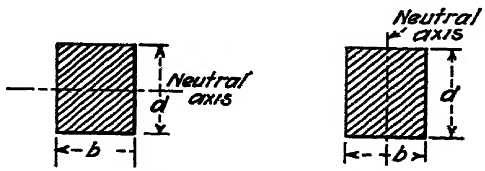
$$\frac{I}{y} = \frac{1}{6}(b - a)d^2.$$

When a pin hole or bolt hole with its axis parallel to the neutral axis is removed from the section, Fig. 189(c),

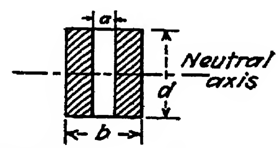
$$I = \tfrac{1}{12}db^3 - \tfrac{1}{12}da^3 = \tfrac{1}{12}d(b^3 - a^3)$$

$$y = \frac{b}{2}$$

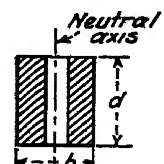
$$\frac{I}{y} = \frac{1}{6}d\left(b^2 - \frac{a^3}{b}\right).$$



(a) Rectangular Cross-section



(b) Hole Removed at 90° to Neutral Axis



(c) Hole Removed Parallel to Neutral Axis

FIG. 189.—Cross-sections of crossarms.

Figure 189(b) represents the condition for stress due to vertical loading, a being the diameter of the pin hole or bolt hole at the weak section. Figure 189(c) represents the cross-section under horizontal loading (dead-end stress, etc.)

Example.—Assume an arm such as that shown in Fig 188 (c) with six wires, the maximum weight of each of which when loaded with ½-in. ice is 150 lb. For a standard six-pin cross-arm,

$$l_1 = 44 \text{ in.}$$
$$l_2 = 29\tfrac{1}{2} \text{ in.}$$
$$l_3 = 15 \text{ in.}$$

Moment about first pin hole from pole $= W_1(l_1 - l_3) + W_2(l_2 - l_3)$
$= 150(29 + 14\frac{1}{2}) = 6{,}525$ in.-lb

For a $3\frac{1}{2}$- by $4\frac{1}{2}$-in. cross-section with a $1\frac{1}{2}$-in pin hole removed,

$$b = 3\tfrac{1}{2} \text{ in}, \; d = 4\tfrac{1}{2} \text{ in.}, \; a = 1\tfrac{1}{2}.$$

$$\frac{I}{y} = \frac{1}{6}\left(3.5 - 1.5\right) 4.5^2 = = \frac{20.25}{3} = 6.75.$$

$$f = \frac{M}{I/y} = \frac{6525}{6.75} = 966.7 \text{ lb per square inch}$$

Double arms, Fig. 187(*d*), are customarily used at dead ends and all points where any considerable amount of unbalanced (longitudinally) load is supported. These are usually placed one on each side of the pole, and fastened together by machine bolts through both arms at the pole, near the ends, and sometimes at intermediate points. Special double-arming bolts threaded full length with nuts on both sides of each arm are quite commonly used as also are wooden blocks or pipe spacers between the arms to hold them apart. If the structure thus formed could be considered as an effective truss, its strength could be computed by using the composite cross-section giving a value of I/y ten or twelve times that of a single cross-arm and hence a strength of ten or twelve times that of a single cross-arm, or five or six times that of two cross-arms without allowance for truss action It has been found by test, however, that the ordinary methods of constructing the double-arm structure do not give an effective truss. The bolts bend or the blocks give way long before such stresses as indicated above are reached.

Some laboratory and field tests made on both single- and double-arm construction have shown the following general results:

1. In general, the arms broke either at the center or at the first pin hole either side of the center. When the grain was very straight, the break was usually sharply across the grain, although in some cases there was shearing on the neutral axis. Where the grain was a little crosswise there was usually shearing, or a diagonal break.

2. For the arms tested the strength seemed to check fairly well the figure of 5,000 lb. per square inch., for ultimate strength of Douglas fir. For vertical loading, *i.e.*, parallel to axis of pin holes the method of taking moments about the center of the arm appears fairly accurate For horizontal load (at right angles to axis of pin holes) the support given by the flat surface of the gain on the pole seemed to have considerable effect on the

strength. The average figure given above was quite closely checked if the moments were figured about the first pin hole rather than the center. For those arms which broke at the center, the unit strength, figuring moments about the center, was much higher than those breaking at the pin hole, indicating that the support of the gain probably reduced the actual stress between pin hole and center. In making these computations allowance must be made for that part of the cross-section cut out by bolt and pin holes.

3. Double-arm construction to be tested was erected with four 4-by 4-in. spacing blocks, one at each end and one at each pole pin. (⅝ in. through bolts through each block, see Fig. 190(*a*).) Theoretically, the strength of such construction might be figured in one of two ways: (*a*) as two single arms, (*b*) as a truss, the spacing blocks being assumed to be rigid.

The latter method would indicate a strength of five or six times that of the former.

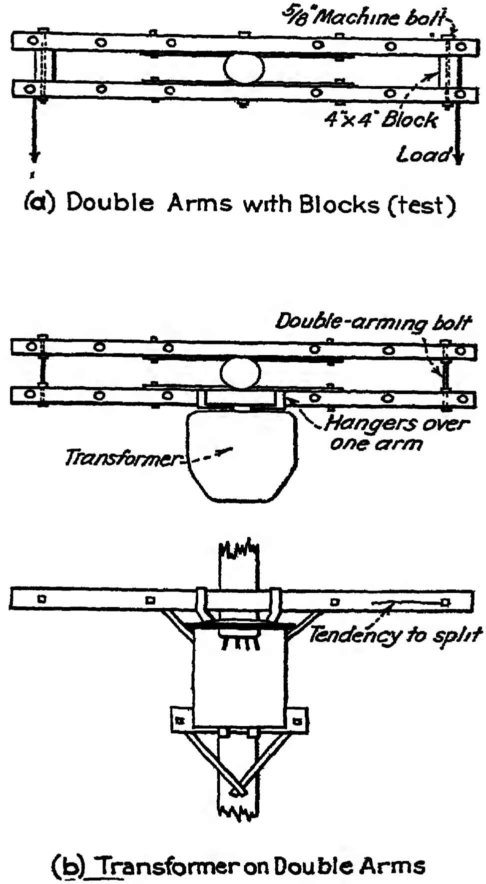


FIG. 190.—Double-arm construction.

The tests made show that the spacing blocks do not hold the construction rigid. Their corners crush into the face of the arms and allow the arrangement to become distorted. The ultimate strength shown was somewhat higher than that of two arms acting independently, but probably not more than 25 to 30 per cent greater on the average.

Another use to which double arms are sometimes put is in hanging heavy transformers, where a single cross-arm is not considered strong enough. If the transformer hanger passes over both cross-arms, the strength of both may be developed,

but in the usual case, where the hanger passes over only one arm, it is doubtful if anything is contributed by the second cross-arm with the ordinary method of double arming. In fact, tests have indicated that such construction is even likely to be weaker than a single arm, since the deflection of the one arm under the weight of the transformer distorts the connecting bolts in such a way as to tend to split both arms apart along their center planes. Since the arm has a tendency to fail by shear along this central plane, the splitting caused by the bolts weakens the structure, see Fig. 190 (*b*). There are, of course, methods of connection which will improve this condition, also other methods of reinforcing transformer installations.

Safety Factors.—Naturally, in figuring the strength of cross-arms, a reasonable allowance must be made for unforseen loads, arms weaker than the ultimate strength assumed, etc. For Grades A, B, and C construction (see Chap. XVI, p. 290), the Safety Code stipulates a safety factor of 2 under vertical loading.

For horizontal loading, no safety factor is definitely specified, it being merely stated that the arms should be sufficiently strong to withstand any unbalanced load to which they are exposed, up to 700 lb. at the outer pin, when conductor pulls are normally balanced. Where sections of Grade A or B line are located in lines of lower grade, it is stated that the arms should be able to withstand, without exceeding their ultimate strength, an unbalanced pull in the direction of the higher grade section equal to the combined tensions of all the conductors supported. Double arms are recommended for such points and also at angles and dead ends for Grade A and B construction. In general, double arms are usually necessary at such points for rigidity, and supply good strength for ordinary spans of light and medium sized wires. For the heavier conductors (No. 0000 etc.), the strength of cross-arms at dead ends should be given special consideration and short, slack spans at such points must sometimes be introduced to relieve the stress.

Hardware.—Typical examples of pole construction are given in Fig. 191 showing the method of attaching the cross-arm to the pole, braces, etc.

Figures 192 and 193 give the dimensions of standards for the various items of hardware shown, as suggested by the Overhead Systems Committee of the National Electric Light Association.[1]

[1] "Overhead Systems Reference Book."

In addition to the above, Fig. 194 (*a*) shows a standard double arming bolt, the use of which is indicated in Fig. 190 (*b*). Figure 194 (*b*) shows a standard eye bolt. These are used for dead ending conductors on cross-arms (when strain insulators are employed), for attaching guys to cross-arms and sometimes to poles, and similar purposes.

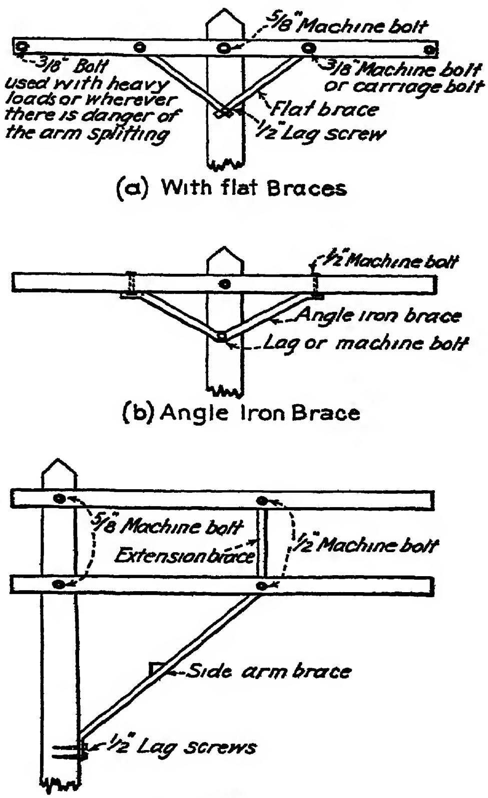


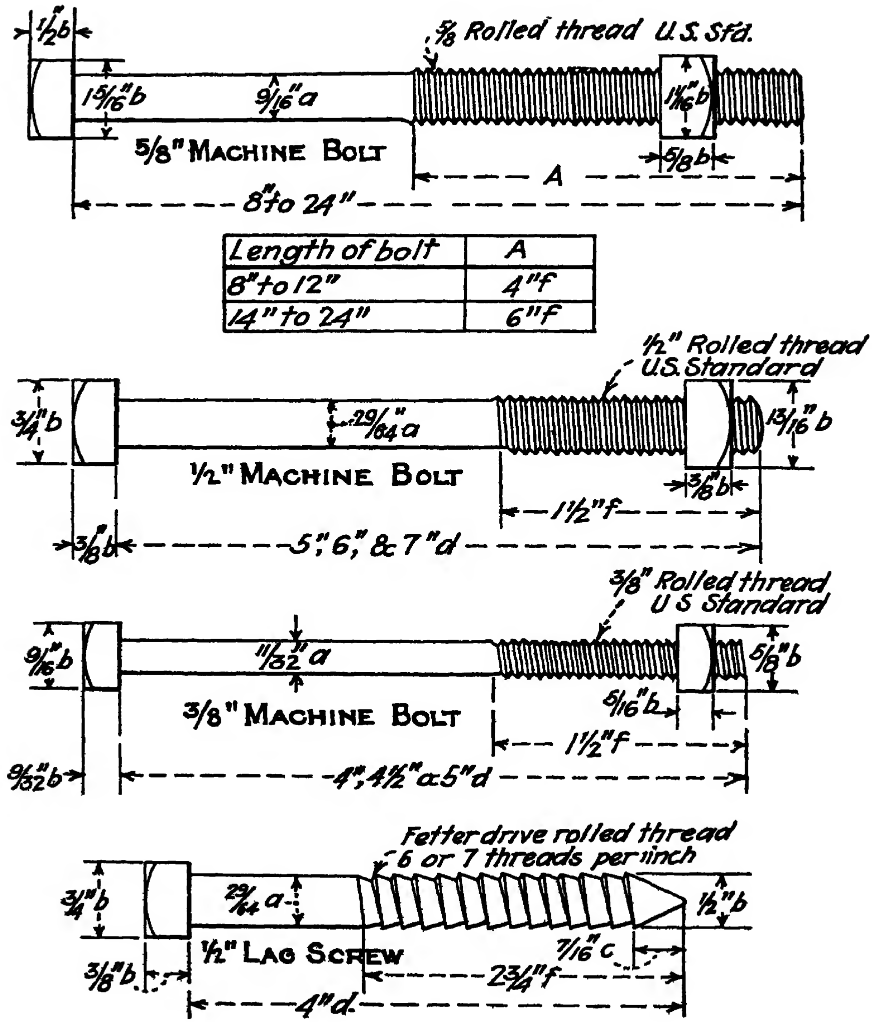
FIG. 191.—Typical crossarm construction.

The strength of cross-arm construction and its stability, especially the latter, depends to a considerable extent on the strength of the hardware used and of the connections made. A few illustrative examples will be discussed briefly.

Bolted Connections.—Wherever load is transferred from one member to another at a bolted connection, as from a cross-arm to a pole or from a cross-arm to a brace, the stress is likely to be largely transmitted to the bolt and from the bolt to the second member. The contact surface between the bolt and either member may be points of weakness, especially if the latter are of wood. Figure 195 illustrates the connection between a cross-arm and a pole. If all the members remained rigid, without any deflection or giving way, and not allowing for the transfer of stress by friction at the plane of contact between arm and pole, the stresses would be distributed somewhat as indicated in Fig. 195 (*a*). W is the vertical load on the cross-arm which is to be transmitted to the pole. This is transferred to the bolt by pressure of the wood of the cross-arm on the upper half of the bolt. The unit pressure is equal to

$$p_1 = \frac{W}{b_1 d}, \tag{75}$$

d being the diameter of the bolt.



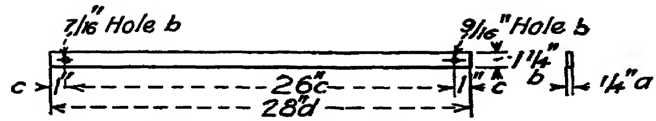
Length of bolt	A
8" to 12"	4" f
14" to 24"	6" f

Material
Steel

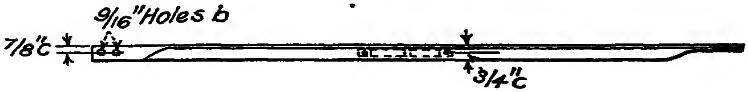
Allowable Variations		
	Over	Under
a	1/64"	1/64"
b	1/32"	1/32"
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"

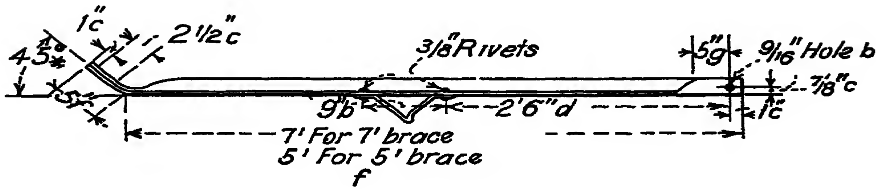
Finish
Hot dip galvanized

FIG. 192.—Hardware—bolts, lags.

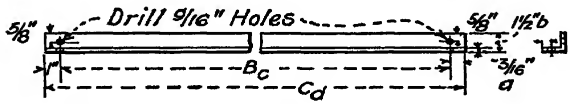


Flat Cross-arm Brace
1/4" x 1 1/4" x 28"



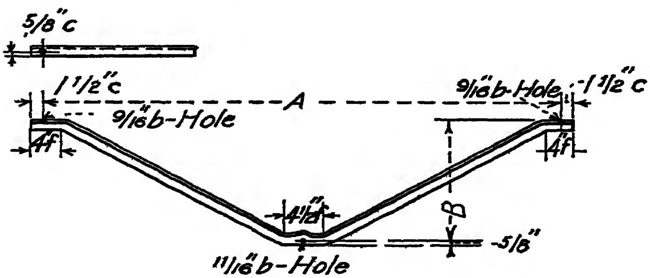


Side-arm Brace
(Size of angle 1 3/4" x 1 3/4" x 3/16")



	2 ft Ext	3 ft Ext.
B	24"	36"
C	26"	38"

Vertical Extension Brace
3/16" x 1 1/2" x 1 1/2" angle
To be used with side arm-brace



A	B
3'-6" c	12" f
4'-0" c	14" f
5'-0" c	18" f

Angle Cross-arm Brace
Size of angle 1 1/2" x 1 1/2" x 3/16"

Allowable Variations		
	Over	Under
a	1/64"	1/64"
b	1/32"	1/32"
c	1/16"	1/16"
d	1/8"	1/8"
f	3/8"	3/8"
*	2°	2°

Material.... Steel

Finish.......... Hot dip galvanized

Fig. 193.—Hardware—braces.

If this pressure exceeds the bearing strength of the wood, the wood will be crushed and distortion, if not complete failure, will result.

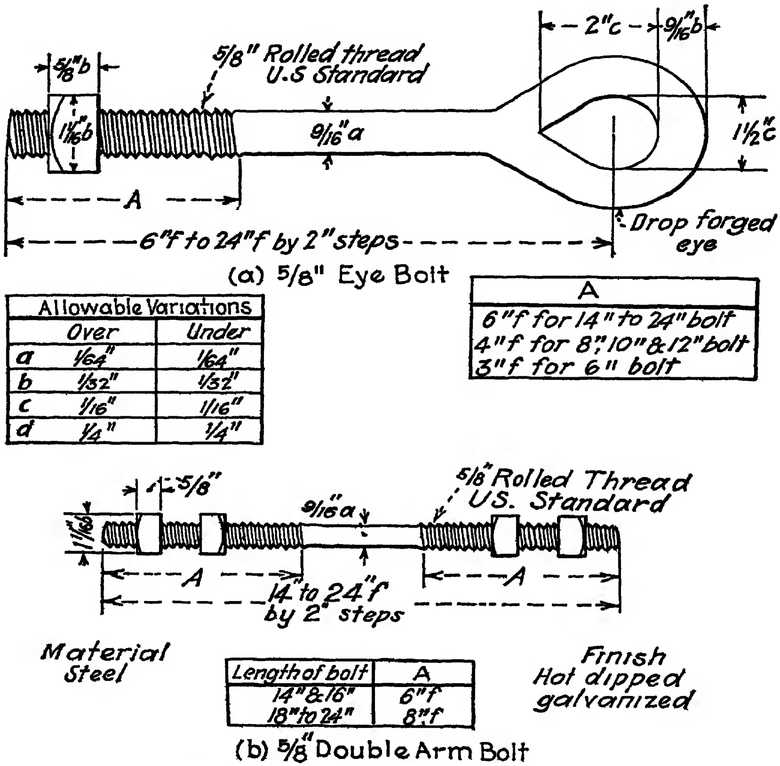


Fig. 194.—Hardware—(a) double-arming bolt; (b) eye bolt.

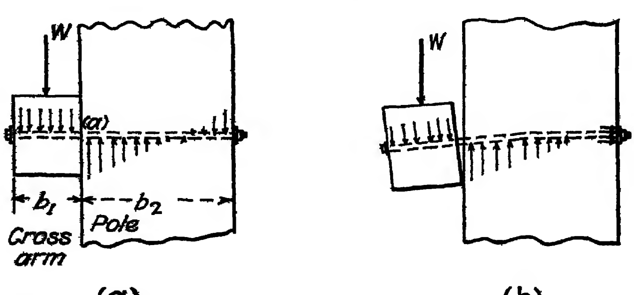


Fig. 195.—Connection between crossarm and pole.

The load is then transferred from the part of the bolt in the cross-arm to the part in the pole with a resulting shearing stress

in the bolt, at the point a, which must not be greater than the shearing strength of the bolt. The load is then transferred to the wood of the pole by pressure along the bolt, maximum unit pressure being

$$p_2 = \frac{4W}{b_2 d}, \tag{76}$$

which must not exceed the bearing value of the wood in the pole, if distortion is not to take place.

Practically, if the bolt is drawn up tight, the contact surface between arm and pole will transfer a considerable amount of the load. When ultimate strength is approached, it is more likely that conditions will be somewhat as indicated in Fig. 195 (*b*). The bearing stress between cross-arm and bolt will tend to be more near the pole than at the outer surface if the bolt bends somewhat and the wood crushes a little. Also, the arm tends to pull away from the pole somewhat under such conditions and the bolt, being in tension, imposes a pressure on the wood of arm and pole through the washers at each end. The exact conditions to be expected under these latter assumptions are very difficult to determine and it is much simpler to compute the strength according to the assumption of rigidity. This method is usually satisfactory if sufficient safety factor is allowed

The ultimate bearing strengths of various timbers are given in Table XVIII.

TABLE XVIII.—BEARING STRENGTH OF TIMBER (ULTIMATE)

Timber	End grain bearing, pounds per square inch	Cross grain bearing, pounds per square inch
Western Red cedar	3,500	700
Northern White cedar.	3,000	700
Southern yellow pine	5,000	1,000
Chestnut	3,500	900
Cypress	3,500	700
Redwood	3,500	600
Douglas fir	4,500	800

For bearing at an angle to the direction of the fibers, the strength may be determined by the formula,

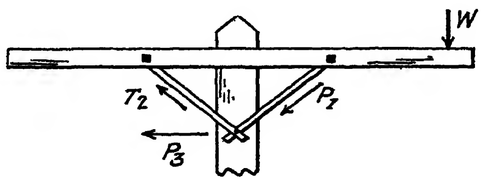
$$r = f \sin^2 \theta + n \cos^2 \theta \tag{77}$$ [1]

[1] N.E.L.A., "Overhead Systems Reference Book," p. 361.

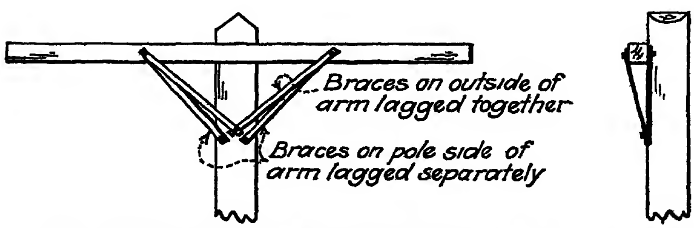
where

r = unit strength on inclined surface,
f = end grain bearing strength,
n = cross-grain bearing strength
θ = angle of inclination of pressure to direction of grain.

Flat vs Angle (One Piece) Cross-arm Braces.—Flat braces, Fig. 191 (*a*), are more commonly used than angle or one-piece braces, Fig. 191 (*b*), but the latter are quite often employed for heavier construction. Something was said previously, in the



(*a*) Stresses on Cross-arm Braces & Lag



(*b*) Cross-arm Heavily Braced for Unbalanced Load

FIG. 196.—Unsymmetrically loaded crossarm.

discussion of loading and stresses of cross-arms, regarding the action of braces and it was brought out that the flat brace was weak in compression (due to its small thickness compared with its length). The amount of support rendered on the compression or load side of an unsymmetrically loaded arm is questionable. The angle brace, being of larger cross-section, is no doubt able to withstand much greater loading in compression. The connection at the cross-arm is also somewhat stronger in that much of the load (on the compression side) is transmitted directly to the brace by pressure of the cross-arm on it. Where the cross-arm is symmetrically loaded and the load is very heavy, the angle brace is somewhat better suited to assist in supporting the arm than the flat braces. Under unsymmetrical loading,

however, the brace is not the weak point of the structure, as a rule. If a cross-arm is loaded on one end, Fig. 196 (*a*), the brace on the load side will be in compression (P_1) and the brace on the other side in tension (T_2) Both of these act on the bolt or lag by which the brace is attached to the pole, applying to it an unbalanced horizontal pressure equal to the sum of the horizontal components of the stresses in both braces (P_3). This pressure must be taken up by pressure of the bolt or lag on the wood of the pole. It will be found in practice that, with the ordinary wooden pole, a single bolt or lag at this point will overstress the wood and cause the structure to be appreciably distorted long before the flat brace on the compression side buckles. Hence the angle brace has no appreciable advantage over the flat brace in keeping the cross-arm horizontal under unsymmetrical load. The bracing shown in Fig. 196 (*b*) has been found to give considerable advantage in this regard, the connection at the pole being materially strengthened.

Where only two flat braces are used, they are sometimes fastened to the outside of the arm, the side away from the pole. While this construction may add somewhat to the horizontal rigidity of the structure, it is probable that the bending of the brace into this position weakens it against vertical loads on the compression side.

Side-arm Braces.—In side-arm construction, the brace must transmit a considerable part of the load on the arm to the pole. With all of the load on the end of the arm beyond the brace, the vertical compression on the brace may be even greater than the load. In any case the actual compressive force on the brace is about 50 per cent greater than the vertical component on account of the angle of the brace. The brace acts as a very slender column. Due to its very large slenderness ratio (of the order of 60 or 70 to 1) the strength is rather difficult to compute, the ordinary formulæ not giving results which agree with field tests. Some tests made by the author on standard (National Electric Light Association) braces showed them capable of withstanding an average ultimate vertical load of about 2,200 lb. for the 7-ft. brace and 3,000 lb. for the 5-ft. brace, the load being applied over the end of the brace. Since the point of attachment of the brace to the arm is considerably nearer the pole with the 5-ft. brace, it should stand more load if it is to have strength equal to the 7-ft. brace in supporting a loaded arm. The ratio of loads

on the two braces for a given moment about the pole is 1.45. Construction with the 7-ft. brace is hence actually somewhat stronger than that with the 5-ft. brace.

Side-arm construction has less rigidity against forces in the direction of the line, hence liberal safety factors should be allowed in the strength of braces. It is often advisable with heavier loads to use two braces with one arm, or two arms with two or more braces. Both 5-ft. and 7-ft. braces can often be used together in such construction to advantage.

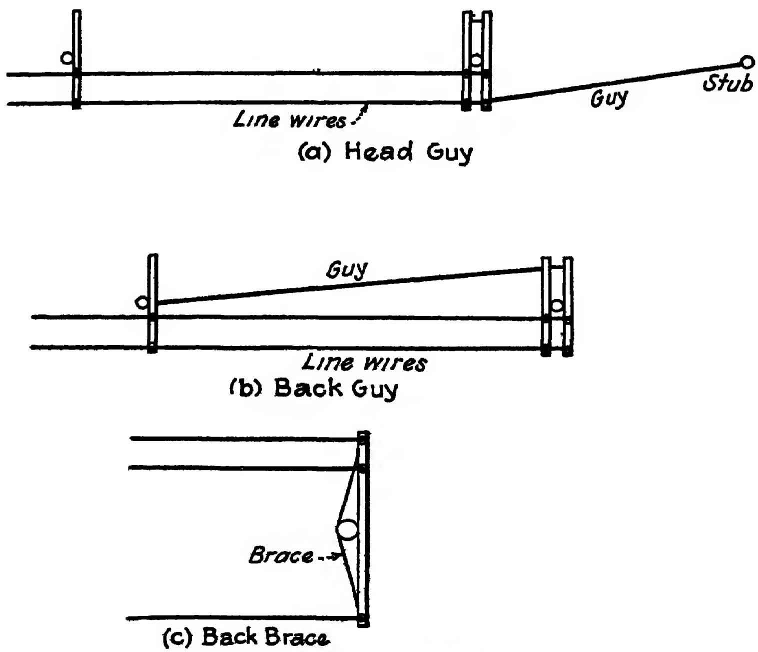


FIG. 197.—Arm guys.

Guying.—At dead ends, if the wires are all carried on one end of the cross-arm (one side of the pole), it is necessary, in order to maintain the arm in its proper position, to guy the arm against the load. This is usually done by attaching a guy to the loaded end of the arm and carrying it ahead to another pole, stub, or anchor. Sometimes, where it is inconvenient to carry the guy in that direction, it may be attached to the opposite end of the arm and carried back to the preceding pole, see Fig. 197.

Where the load is equally balanced on both ends of the arm, arm guys are ordinarily unnecessary unless the load is sufficient

to overload the arms. In such a case arm guys at both ends of the arm will be necessary. Where the load is only partially unbalanced, arm guys should usually be used, although for small unbalances (equal to the tension of one small wire near the pole for example), the ordinary, double-arm construction is sufficiently rigid to maintain itself in position. Just where the line should be drawn is largely a matter of experience and no general rule can be given.

Where single arms are used with unbalanced dead-end loading, it is sometimes the practice to use a steel back brace running from the end or middle of the arm to the pole. This sort of structure has relatively little rigidity, compared with one guyed and is not generally used except for service buck arms, see Fig. 197 (*c*).

Steel Cross-arms.—Steel cross-arms belong in much the same category as steel poles for distribution work, having similar advantages and disadvantages. Where steel poles are employed, steel arms are often advisable but are not always used. In general the steel arm, although probably having longer life is more costly, is heavier to handle, and does not have the insulating value of a wooden arm. With the present plentiful supply of cross-arm timber, the field for steel arms is necessarily quite limited.

CHAPTER XVIII

SECONDARY RACKS

Secondary racks have come to be very commonly used instead of cross-arms for supporting low-voltage wires on poles. The rack consists essentially of a steel back, attached to the pole, upon which are mounted the insulators which support the secondary wires, and to which are also attached the service wires branching off to customers along the line. The racks are mounted vertically, *i.e.*, with the insulators one above the other. There are several marked advantages in this type of construction:

1. The wires being in a vertical plane, secondary service wires running in different directions do not cross each other, see Fig. 199.

2. If properly designed and erected, the rack construction has better strength than cross-arm construction and is not subject to being pulled out of position as is a service buck arm.

3. Rack construction is, as a rule, more economical than cross-arm construction. The rack with its insulators usually costs little if any more than the corresponding cross-arm with its pins, insulators, and braces. At the same time, an appreciable number of cross-arms are eliminated, since corners may be turned on one rack, where two sets of double arms would be required, and wires may be dead ended on one rack instead of double arms. In addition, the labor cost of rack construction is usually somewhat less than that with cross-arms.

4. The rack construction is considered by most people to have a neater appearance than cross-arm construction.

Of course there are certain conditions where cross-arms serve the purpose better than racks. Where clearance above ground or other wires is limited, the cross-arm, since it carries the wires in a horizontal plane, occupies less pole space than the rack. If service wires are few and can be taken directly off the line insulators, this may be a real advantage. Where there are many service wires however, requiring a separate buck arm below the line arm for attaching them, the rack, placed with its top where the arm

would be, occupies little if any more pole space. A further consideration of this same sort is that, where pole space is limited, it is sometimes easier to provide climbing space (see Chap. XXIII) with cross-arms than with racks. According to the Safety Code, unless the rack is 4 ft. below the next arm above it, full climbing space must be provided past the rack and the arm which, with the standard six-pin arm, requires the pole pin on the arm on the side opposite the rack to be left vacant With cross-arm construction, the secondary arm is often placed 2 ft. below the primary arm and climbing space through both is quite easily provided These points are not always of serious importance however, since sufficient space on the primary arm is often available for allowing the climbing space mentioned, and also some companies find it advisable to place the secondary 4 ft, below the primary in either case, as a standard practice. Hence, although the rack has some limitations to its use, it is quite generally recognized as a useful and economical piece of equipment.

Types of Secondary Racks.—There are two general types of secondary rack in use, the spool type and the knob type These are illustrated in Fig. 198. The former was the type originally used and is more prevalent at present. The knob type is favored in some quarters, however. On the spool type, the line wires are carried on the side of the spool (either the inside or the outside) held on by a tie wire, and the service wires are held by being passed around the spool also, see Fig 199(*a*) On the knob type the line wire is laid in the groove on the top of the insulator, held by a tie wire of course, and the service wires pass through the hole in the insulator, see Fig. 199(*b*).

The spool type has the advantage of being easy to assemble and disassemble, making it possible to change a broken insulator without removing the rack from the pole. The insulators are of simple form and are a standard with most porcelain companies, being available in either wet- or dry-process porcelain. They have the disadvantage, however, of having usually to be disassembled when being mounted if the mounting bolts are placed under or between the insulators, or else the bolts must be placed beyond the end insulators. In the latter case, the rack is likely to be structurally weak at the center due to the long span between bolts. Another disadvantage is that the usual method of failure when tested to destruction is by the insulator being broken due to

bending in the bolt long before it has developed its full strength in compression.

The knob type has the advantage of being assembled once and for all in the factory and can be handled thereafter as one piece. It can be easily erected with bolts through holes between the insulators without disassembling If properly designed, it may

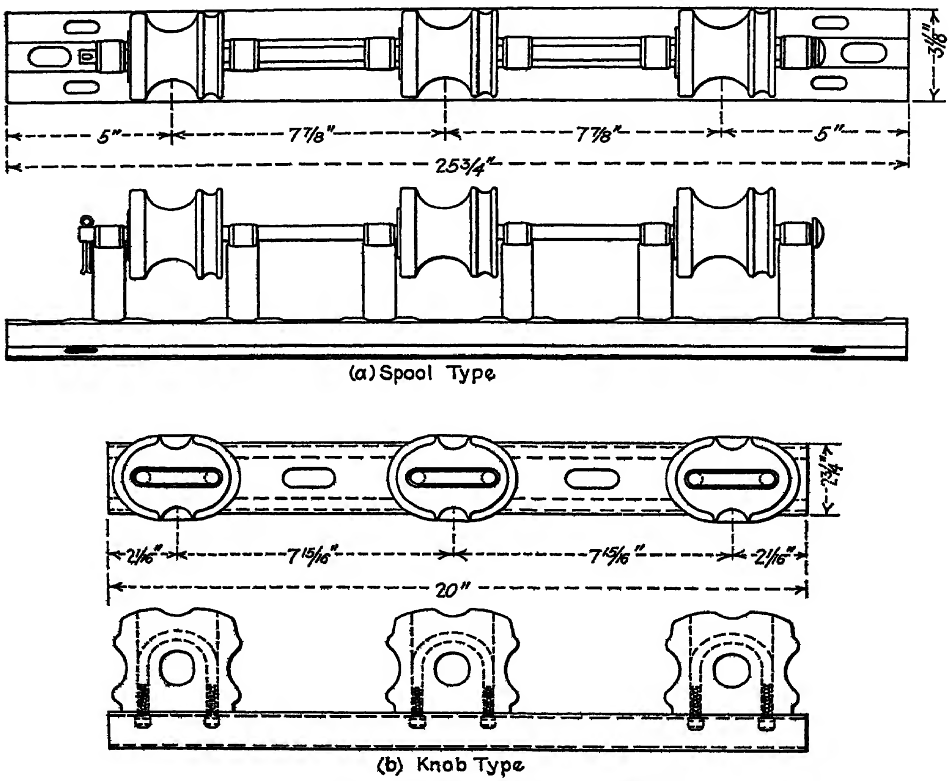


Fig. 198.—Types of secondary racks.

develop more nearly the full compressive strengths of the porcelain in the insulators, since failure is not dependent on the deflection of the steel frame. For this reason, it is more likely to have greater ultimate strength under dead-end loading than the spool-type rack of equal weight (of any of the present standard designs). The position of the line wires on top of the insulator makes it possible to carry larger wires more easily without interfering with service wires and also facilitates the replacing of the line wires when necessary. The disadvantages of the knob rack are

that the insulators are of more special and complicated shape than the spool and have, as yet, been in no sense standardized. Where it is necessary to thread the conductors through the insulator, as at corners and dead ends, it is somewhat more difficult to do than with the spool. This type is more recent and has been less used than the spool type and hence has not been so well proved by experience.

Secondary racks are made usually to accommodate three wires, *i.e.*, with three insulators, but are also made for two wires and for more than three if required. The spacing between insulators is sometimes 4 in., sometimes 6 in., and sometimes 8 in. The smaller spacings make a more compact rack and hence one somewhat stronger for the same number of wires and one which occupies less pole space. The better clearance between wires offered by the larger spacing is quite an advantage in working on them, however, and the 8-in. spacing is probably used somewhat more than the others on that account.

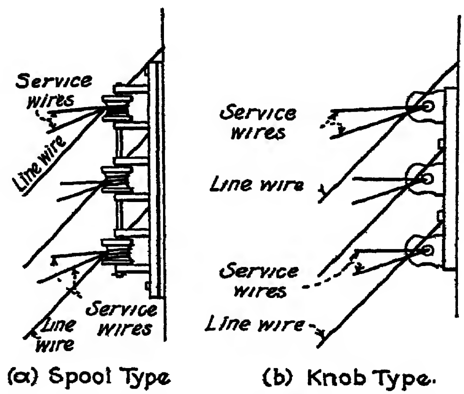


FIG. 199.—Attachment of wires to racks.

Racks are made either with extended backs so that the fastening bolts may be placed beyond the end insulators or simply with bolt holes between the insulators (or under the insulators in some cases). In the latter case, with the spool type it is generally necessary to disassemble the spools from the rack when attaching it to the pole. The knob type is generally made without the extended back, as the chief reason for it is avoided.

Typical Construction with Racks.—A few details of typical construction with secondary racks are shown on Fig. 200. The distance between the top of the rack and the next cross-arm above it differs with different companies. Two feet is the minimum where the arm carries primary wires (according to the Safety Code) but this limits the use of the primary arm on account of the climbing space requirement as previously mentioned and also is somewhat small for good working conditions. Four feet is a convenient distance, being sufficient so that no special provision need be made for climbing space on the arm

above, and giving fairly good clearance for working on the wires above. Greater distances, such as 6 ft. are also sometimes used for extra clearance. It is sometimes the practice to keep the secondaries on racks on a fairly even level on all poles where

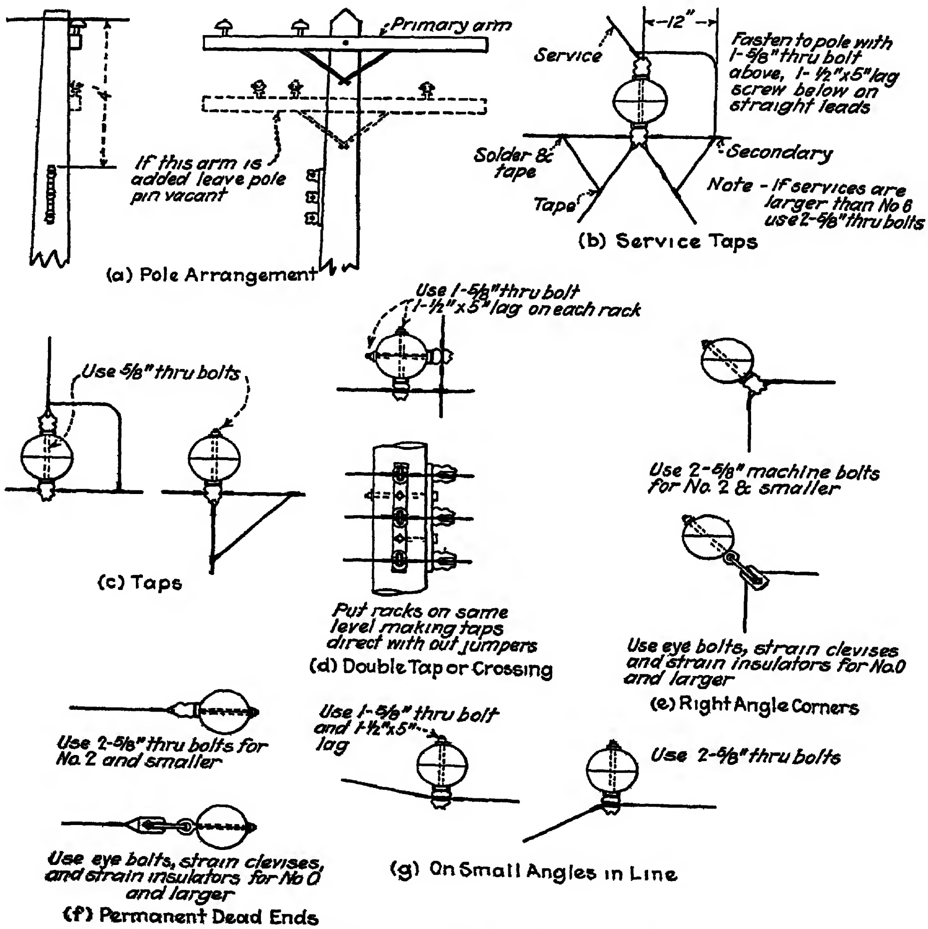


FIG. 200 —Typical construction with secondary racks.

possible, even though the primary must be raised (by taller poles) to clear trees, etc.

For ordinary straight-line work, racks are usually fastened to the pole with one machine bolt and one lag, although two machine bolts are sometimes preferred. Where only one bolt is used, it is placed in the upper position with the lag in the lower, Fig. 200(*b*).

At corners or dead ends where the rack must support dead-end tension, bolts only should be used. Where the tension is heavy, more than two bolts are sometimes advisable if the rack is so designed that they may be used. The number of bolts required depends upon the strength and design of the rack as well as on the load. At points where sufficient dead-end strength cannot be obtained with the rack, as with very heavy wires, it is common practice to use strain insulators, fastened to eyebolts through the pole, Fig. 200(*e*).

The method of wiring services is shown in Fig. 200(*b*). Where services are run on the opposite side of the pole from the line rack, a second rack may be used on the same level, the same bolt or bolts being used for both.

Loading and Strength.—Secondary racks are subject to loading of three different sorts, *i.e.*, in three different directions. It is important that the strength of any rack under all three be considered and that it be not weak in any one.

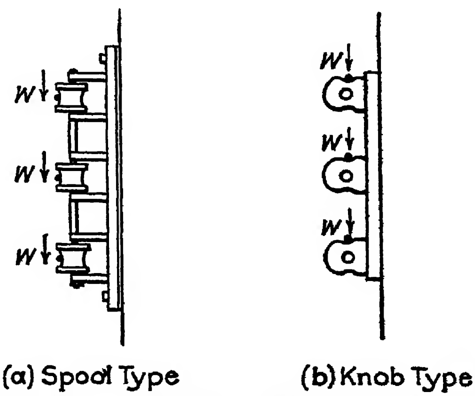


FIG. 201 —Loading on secondary racks—vertical

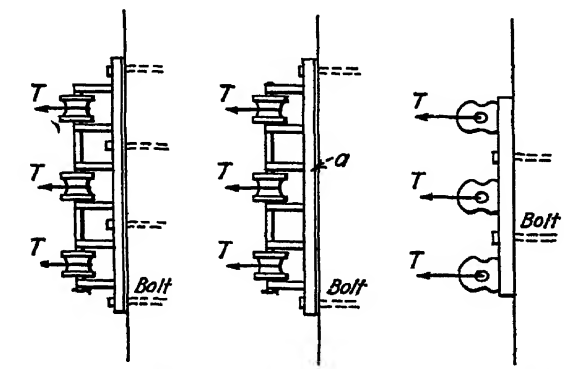
The weight of the wires supported, including ice loading, and also including the weight of service wires carried, imposes a load in a vertical direction or parallel to the back of the rack in its normal position. This is indicated in Fig. 201. With the spool-type rack, this load is carried by the arms supporting the insulators, acting as cantilever beams, the load being transmitted to them by the spools resting on them. All of the arms do not receive load, the ones above the insulators (on racks with 6- or 8-in. spacing) not being affected except that the top one may receive part of the load from the lowest one through the axial bolt. This load may reach considerable proportions if heavy wires are carried. A rack may be quite strong in other directions and yet be weak under such loading since these arms are ordinarily made of comparatively light cross-section, even of flat straps in some cases. With the knob-type rack, the vertical load is transmitted to the back by shear on the bolts fastening the insulators to the back, provided the insulators do not crush at

any point or pull away from the back. In the latter case a considerable amount of stress may be concentrated at the lower edge of the insulator.

The second type of load on the rack is that due to the tension in the line wires at corners and dead ends, and the tension in the service wires where such are taken off at these points and elsewhere. Just what such loading will amount to depends on the size of wires, the wind and ice loading, and the spans and sags used. Data for various sizes of wires may be obtained from Chap. XXII. For example, if No. 0000 medium hard copper secondary wires were dead ended under conditions where the maximum loading would stress the wire up to 50 per cent of its ultimate strength (approximately its elastic limit), the pull on the rack for each wire would reach values of about 4,000 lb. This, of course, is rather extreme, but the sags recommended in the Safety Code for such wire under ordinary conditions would give a tension of 2,000 to 2,500 lb. under maximum assumed loading. No. 2 medium hard copper, a common size for secondaries, would give a tension of about 1,200 lb. under similar conditions. Considering light service wires, a No. 8 soft drawn copper wire has an ultimate strength of 480 lb. and its elastic limit is about 240 lb. Service wires are usually strung with more sag than line wires, but it may be assumed that such a wire might well have a tension of 100 to 150 lb. when loaded. If there were four three-wire services taken off the rack, the total pull on each insulator would be from 400 to 600 lb. These figures are merely given as examples of what the magnitude of loading might be. For any particular case the loading should be worked out for local conditions as to size and probable number of wires, etc. It should be emphasized however, that such loading is of appreciable magnitude in any case and the rack should be strong enough to withstand it.

The strength of the rack in service will depend not only on its design but also on the way it is mounted. If a bolt is placed under each insulator (as is the practice with some types of racks) or on both sides of each insulator, see Fig. 202 (*a*), the strength of the back itself has comparatively little bearing, the stress being transmitted almost directly to the bolts. In this case, the limiting strength will usually be that of the insulator, either in compression from the wire itself or under stresses imposed by the distortion of the steel bolts or arms supporting it. With the spool-type rack, it is usually more convenient to mount it

with end bolts only, Fig. 202 (*b*), as these can be inserted without taking the rack apart. The rack in this case acts as a comparatively long beam, supported at both ends, with the load applied at six points, *i.e.*, where the arms are attached to the back. The point of greatest stress in the back (with symmetrical loading) is where either of the arms supporting the middle insulator are attached (*a* in Fig. 202 (*b*)), the bending moment being greatest at that point. In some designs of racks, the back is weakened at that point by the method of attaching the arm, *i.e.*, rivet holes are cut in it or it is slotted and the arm laced through it. Such racks are usually comparatively weak when mounted in this



(a) Bolt each side of each Insulator (b) End Bolts only (c) Knob Type bolts between Insulators

FIG. 202.—Loading on secondary racks—horizontal.

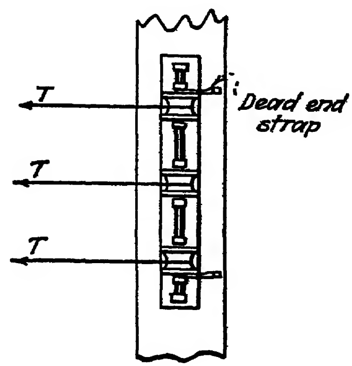


FIG 203.—Loading on secondary racks—side pull.

manner (bolts at the ends) but may be sufficiently strong when more bolts are used as in Fig. 202 (*a*). The bolt through the insulators adds some strength to the rack in bending but it is usually by distortion of this bolt that failure takes place, the bending of the bolt breaking the spools. Where the two mounting bolts are placed between the insulators, as indicated for the knob rack in Fig. 202 (*c*), the rack acts as a composite beam, the two ends being in cantilever and the point of maximum stress being at the point of support. Here again the back is, with some types, somewhat weakened by the bolt hole. The maximum bending moment with such mounting is considerably less, however, than for end mounting, being, for a rack with 8-in. spacing, only about one-half as great.

The third type of loading is side pull on the rack due to dead-end tension, if the rack is mounted on the side of a pole at a dead end, or due to the unbalanced pull in case of broken wires, see Fig. 203. The strength of the rack under such loading, limited

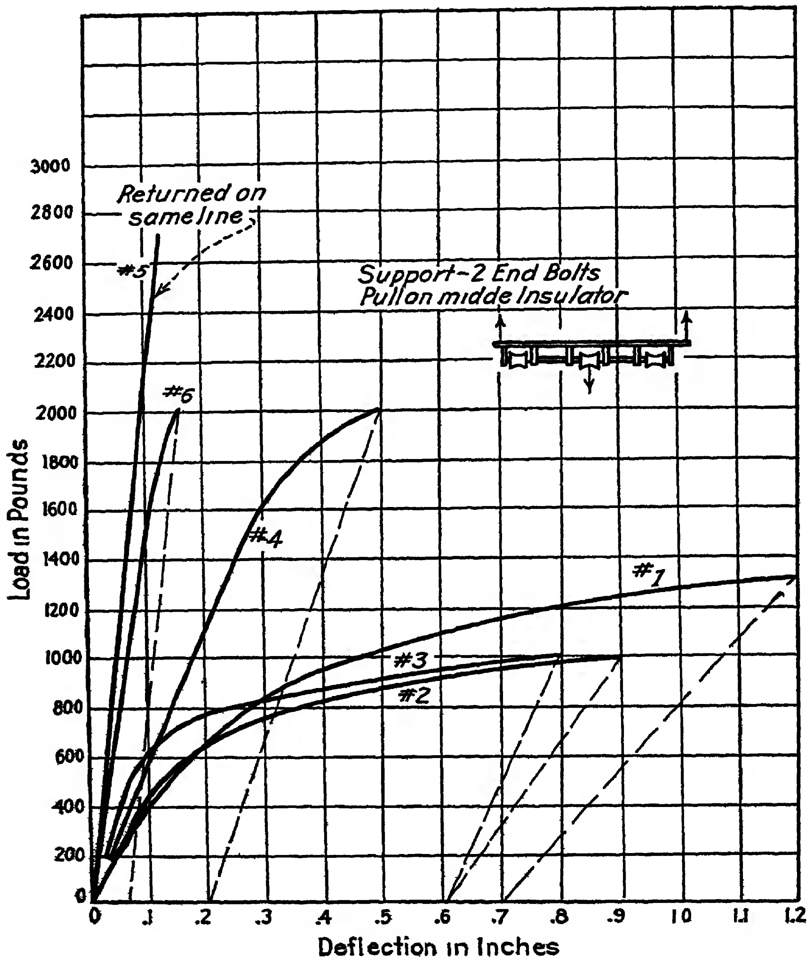


Fig. 204.—Results of strength test on secondary racks.

by the strength of the attachment to the pole, is likely to be small compared with the strength of the rack under direct pull as discussed above. It is usually preferable to place the rack on the face of the pole at dead ends as shown in Fig. 200 (*c*). With the spool rack, "dead-end straps" are sometimes used at

dead ends with the rack in its normal position on the side of the pole, the straps being slipped over the axial bolt and lagged back to the pole on the side away from the pull (Fig. 203).

Stresses are also imposed on the backs and on the bolts attaching the rack to the pole but usually the racks are comparatively strong at these points. It is very difficult to predetermine the strength of a rack by computation. Laboratory and field tests should be carried out on the complete rack to determine its strength.

The strength of any particular rack can best be determined by actual test, simulating field conditions as nearly as possible. The author has made quite a number of such tests, with results varying from less than 200 lb. per insulator to very nearly 4,000 lb. per insulator at the elastic limit of the rack, mounted and loaded as in Figs. 202 (*b*) or (*c*). When mounted as in Fig. 202 (*a*) the ordinary dry-process spool insulator usually stood in the neighborhood of 2,000 to 2,200 lb. before breaking. In comparing different designs of racks and different methods of mounting in such tests, it was found very convenient to plot a stress deflection curve for each, thus exhibiting the relative stiffness, elastic limit, etc. Figure 204 shows typical curves resulting from such test.

The relative proportion between stress and strength which should be allowed for a rack is more or less a matter for the application of good judgment. Where the loading assumed is that due to conductors stressed to their elastic limit, not much safety factor should be necessary ordinarily, since the conductors will stretch before the tension can be increased materially. Under other assumptions of loading, a safety factor of 2 is perhaps reasonable. The Safety Code does not stipulate any definite provision in this regard except, in general, that pins and other conductor fastenings should be able to withstand an unbalanced tension in the conductor up to 700 lb. per pin or fastening, where Grade A, B, or C construction is required.

CHAPTER XIX

PINS AND BRACKETS

Except for secondary rack construction, described in Chap. XVIII, overhead line conductors are carried on insulators (see Chap. XX) which are supported by pins of some sort threaded or cemented into them, which pins are in turn attached to a cross-arm or directly to the pole itself. The commonest form of pin is that used with a cross-arm, having a threaded section at one end which fits the threads on the inside of the insulator, a supporting section below that of sufficient length to hold the insulator at the proper height above the arm, and a shank end which fits into a hole in the cross-arm, the whole being of sufficient strength to adequately support the imposed loading. There are many other types of pins, or brackets as they are sometimes called, however, and some of the commonest of these will be discussed briefly in addition to this commonest form.

Material.—Pins are made of either wood or metal. For the metal types, the materials most commonly used are steel and malleable iron. Wood pins are more generally used for distribution construction than metal pins, although the latter have their advocates. For voltages above about 13,200, metal pins are quite commonly used although wood pins are used for higher voltages (up to 50,000 volts) in some places. The advantages claimed for metal pins are their comparatively longer life than wood pins, and their more uniform strength. It is also sometimes assumed that the metal pin will naturally be stronger than the wood pin. This is not necessarily true, its strength depending on its size and design. A number of the common types of metal pins will be found to have materially less strength than the wood pins which they are intended to replace. In choosing a metal pin, careful attention should be given to this factor and its strength determined by test if there is any question. As to the advantage of longer life, where wood poles and cross-arms are used, it is not necessarily an

economy to use pins whose life will be longer than that of the poles and arms. A good wood pin has usually fully as long life as a wood cross-arm and when replacement of the latter becomes necessary, depreciation or obsolescence of the pin will very often prevent its being reclaimed, even though it may have considerable useful life remaining Since the metal pin usually costs several times as much as the wood pin, its economy can be questioned. Where steel cross-arms and poles are used, this consideration, of course, is changed. The advantage of greater uniformity in strength in the metal pin is, of course, a real one, wood pins varying considerably from the average. Another advantage of metal pins is that, as a rule, they require a much smaller hole through the cross-arm than the wood pins, thus conserving the strength of the arm. This may sometimes be an important factor where loads are heavy. It quite often happens, however, that the standard cross-arm has a large safety factor under the loading imposed and the extra strength gained by reducing the size of pin hole is not of great value. One advantage of the wood pin is the fact that it has a considerable amount of insulating value.

Wood Pins.—The most commonly used timber for wood pins is yellow or black locust. This wood has the qualities of high fiber strength, extreme toughness, and great durability. A sound piece of locust will rarely break sharply when tested to failure. It will usually stand a large amount of distortion and, even after partial failure, will hold together and sustain a large percentage of the maximum load. The strength and toughness probably decrease somewhat with age although the amount or the rate of change is not known. A large proportion of the strength is retained, however, for many years, the useful life probably averaging at least 15 years under favorable conditions.

The fiber strength of locust (ultimate) is given as approximately 10,000 lb. per square inch (in bending).

Any considerable number or amount of defects should not be allowed in a wood pin, especially in the section of the pin above the cross-arm. Such defects are crooked grain, large checks, loose or unsound knots (or any knots greater than ⅛ in. in the section above the cross-arm), sapwood of any appreciable amount, wormholes, pitch pockets, etc.

Other timbers are sometimes used for wood pins and some of these may have as favorable qualities as locust, but none of

them have been as generally accepted, on the basis of tried experience, for this purpose Oak has been used to some extent and has the qualities of strength and toughness when new but apparently has a tendency to become brittle with age.

Metal Pins.—Steel pins are made from solid forgings, hollow tubing, pressed steel shapes of various kinds, etc. Some of these will be illustrated later.

Malleable-iron pins are usually in the form of solid castings, sometimes of circular cross-section and sometimes of other shapes designed to make better use of the metal. If properly made, malleable iron has good strength and durability. Improper manufacture may introduce an undesirable brittleness in the material. Modern processes in the better plants are designed to prevent such defects however.

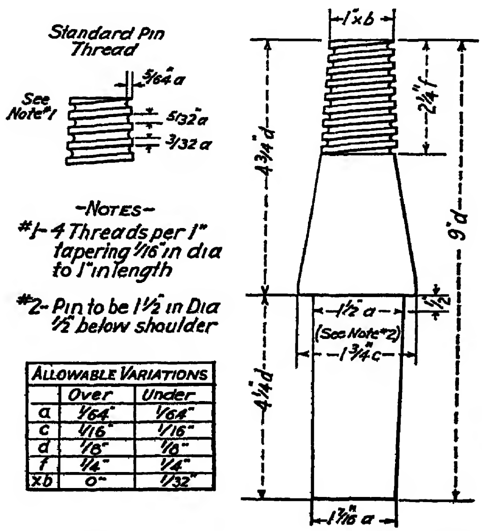


Fig. 205.—Wood pin (*N E.L.A.* suggested standard).

With either steel or malleable iron it is quite essential that the surface of the pin be galvanized or otherwise protected against corrosion. Hot-dip galvanizing is used almost entirely for this purpose with pins and is an efficient protection.

The fiber strength (ultimate) of these materials in bending is given as:

Steel, 60,000 lb. per square inch

Malleable iron, 50,000 lb. per square inch.

Typical Designs.—Wood pin design commonly follows, or at least is quite similar to the suggested standard of the Overhead Systems Committee, National Electric Light Association[1] which is shown on Fig. 205.

A series of tests on wood pins of various designs, which are further described below, indicated the desirability of using as thick a cross-section as practicable in the portion above the shoulder up to the threads, and of reducing the number of

[1] "Overhead Systems Reference Book," p. 516.

threads as much as possible. A design based on these suggestions, which may be used where the number of threads indicated are sufficient for the insulators used, is shown on Fig. 206. It is believed that this will have somewhat greater strength than the standard.

A number of typical designs of metal pins are shown in Fig. 207. The problem of threads on such pins has been met in several different ways as indicated on these pins, a solid metal thread being impracticable on account of the dissimilar expansion of

ALLOWABLE VARIATIONS		
	Over	Under
a	1/64"	1/64"
b	1/32"	1/32"
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"
xc	0	1/16"

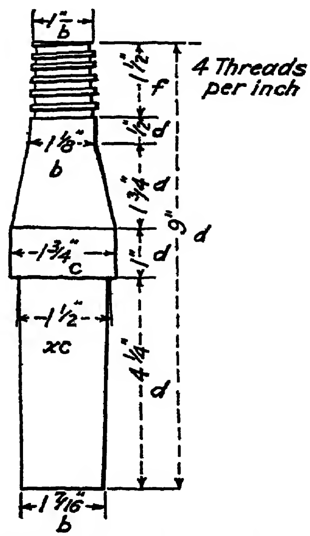


FIG 206.—Variation of wood pin to increase strength.

steel or iron and porcelain or glass with rise in temperature. In general these types of threads are as follows:

1. Simple splitting of end or cutting out section across pin for a distance from the end, virtually making the threaded section in two separate portions (used with malleable-iron pins). This is likely not to furnish sufficient flexibility, the threaded sections being still very rigid.

2. *Cast-lead Threads.*—This is a quite satisfactory solution. The lead being comparatively soft adjusts itself readily to inequalities in the porcelain threads and to changes in temperature.

3. *Wire Wound Spirally to Form Thread.*—This makes a satisfactory thread if the wire is properly anchored at the ends.

It does not insure the insulator, being held as rigidly in its proper position as some of the other methods if such a quality is essential.

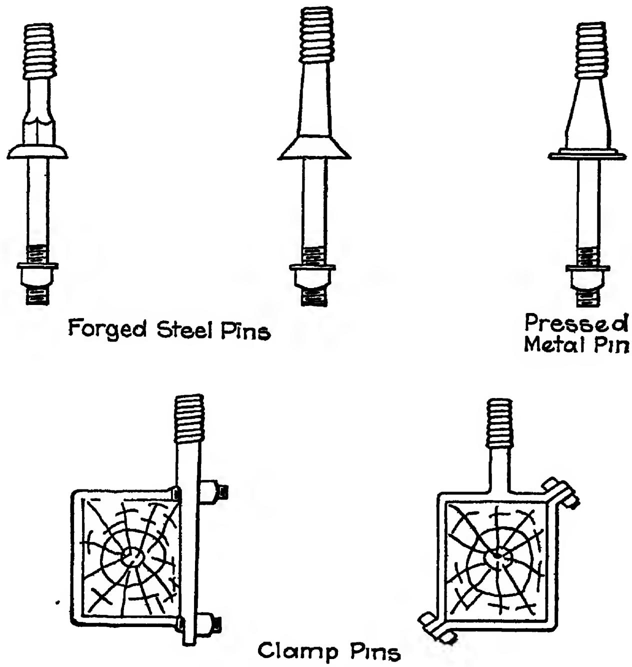


FIG. 207.—Typical metal pins.

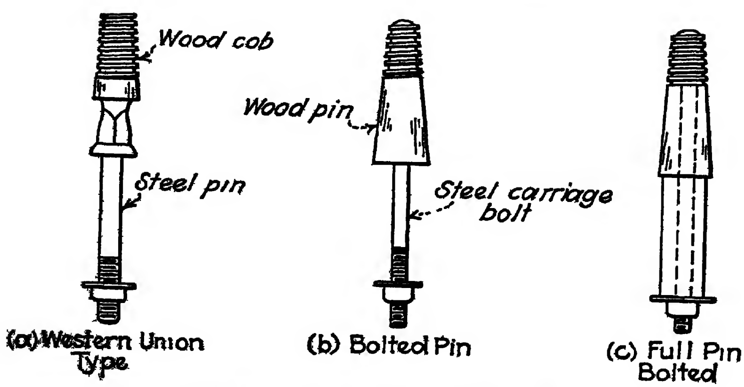


FIG. 208.—Wood and metal pins

4. *Pressed-steel Threads Welded to Pin.*—This also is a satisfactory thread if properly manufactured, it being necessary

that the threads be very carefully aligned in assembly and that the weld be well made.

Combinations of wood and metal are sometimes used for pins. The chief examples of this are metal pins with wood cobs or threads on the end, and wood pins with steel bolts inserted axially through them, see Fig 208. The former is, essentially, merely another solution to the problem of threads on the metal pin as has been discussed. It is used to a large extent on communication lines where the individual wire load is relatively small, but not a great deal on distribution circuits. The latter type, Fig. 208 (*c*) has been sometimes used with the false belief that it was a stronger pin than the plain wooden pin. This is usually not true, however, the bolt being placed at the point of minimum stress in the pin (the neutral axis) and hence not taking any appreciable part of the load unless of large enough diameter to have an effective strength of its own, which is usually not practicable. In fact, the cutting out of the axial hole in the pin will usually weaken it more than any strength it may gain from the bolt.

Loading.—The loads on a pin are those imposed by the weight of the wire supported, acting vertically downward, the wind

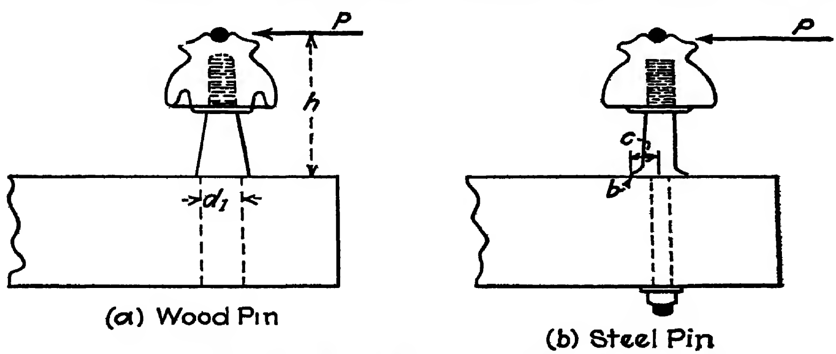


FIG 209.—Illustrating loading and stress in pins

pressure on the wire, acting horizontally at the end of the pin, and the tension in the wire, acting also horizontally at the end of the pin at dead ends and corners and under broken-wire conditions. The amount of such loading may be derived from the data given in Chap. XXII on "Conductors."

Under the vertical load, the pin acts as a simple column, transmitting the load to the cross-arm at the shoulders where it rests upon the arm (or in other types, through the bolts attaching

it to the arm, etc.). This stress in the pin due to one component of the total load is usually not large compared with that resulting from the other components. It equals the vertical load divided by the area under pressure (either the cross-section of the pin or the area of the shoulder resting on the cross-arm).

Under the horizontal load, either of side-wind pressure on the wire or of tension in the wire, the pin acts as a cantilever beam. The maximum stress is considered to be at the point where the pin enters the arm (or other point of attachment) and the bending moment at that point equal to the load times the distance of the *conductor* above that point,

$$P \times h \text{ in Fig. 209.}$$

Strength.—The computation of the strength of a pin in a cross-arm is rather uncertain, due to the rather indeterminate action of the support. For example, the wood pin in Fig 209 (*a*), might be considered as rigidly held in the arm and the strength figured as that of the cross-section of the shank *d* (under the shoulder) under the cantilever stress of $P \times h$,

$$f = \frac{P \times h}{0.0982 d_1^3} \tag{78}$$

However, it is recognized that the shoulder gives more or less support according to its width and bearing. Also, the pin is not always a tight fit in the hole. Both of these factors alter the strength from that obtained theoretically.

If the pin is of the design shown in Fig. 209 (*b*), the action may be considered as a balancing of moments about the point *b*, the strength of the pin being that of the bolt in tension acting through the lever arm *c*. Here again, if the arm is of wood, a crushing is likely to take place at *b* which will materially affect the strength.

In either of these cases, especially the latter, the cross-section of the pin at some point above the arm may be the weak point. The stress would then be obtained as indicated in the formula above (for a solid circular cross-section), using the diameter at the weak point instead of d_1.

For a metal pin of hollow cross-section, the equation above would of course become

$$f = \frac{P \times h}{0.0982\left(d^3 - \dfrac{d_a^4}{d}\right)} \tag{79}$$

where

d_a = inside diameter at point where outside diameter is d

A series of strength tests on a fairly large number of wood pins, of design quite similar to the National Electric Light Association standard pin, Fig. 205, indicated that failure of such pins under load applied at right angles to the axis usually takes the form of a shearing along a plane parallel to the axis of the pin, starting in the lowest thread and running to the shoulder as indicated in Fig. 210. This is probably due to the concentrated shearing stress at the base of this thread, the tensile stress on the outside fibers changing from a comparatively large amount to zero in an indeterminably short distance at that point. It was deduced from this that one method of making a stronger pin would be to reduce the number of threads as much as possible, using only enough to fit the number in the insulators to be used. It was also indicated that it was desirable to carry the diameter just above the shoulder up as far as practicable (without interfering with the insulator) to increase the stock in the pin. A pin was designed on this basis, see Fig. 206, using only six threads, and further tests made seemed to bear out conclusively that the strength was materially increased by these changes. Of course, where insulators with long threads are used, the reduction in number of threads is impossible, but many of the present standard insulators require no more than six or seven threads (see Chap. XX). Other methods of increasing the strength of a pin are by increasing the diameter at the top (threads) and by increasing the diameter of the shank, but both of these get away from the accepted standard for small pins. For higher voltages the 1⅜-in. top pin is quite usual.

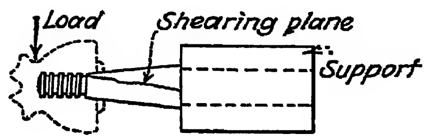


FIG. 210.—Typical failure of wood pin under test.

The Safety Code prescribes that for Grades A, B, or C construction, a pin shall have sufficient strength to withstand an unbalanced tension in the conductor up to a limit of 700 lb. per pin. The tests mentioned indicated that the standard locust pin would average at least that amount, although individual specimens showed less strength in some cases, even without apparent defects. The side-wind pressure on a span of wire 150 ft in

length covered with ½ in. of ice, at 8 lb. per square foot, is only 180 lb. for No. 0000 stranded T.B.W.P. wire, so a pin with 700-lb. strength has ample safety factor against such loading. Under dead-end conditions, however, the stress is much greater. Using the sags given in the Safety Code, in a 150-ft. span, the tension under maximum loading (heavy) would be 2,650 lb. for No. 0000, 1,600 lb for No. 0, 1,200 lb for No. 2, 760 lb for No. 6,

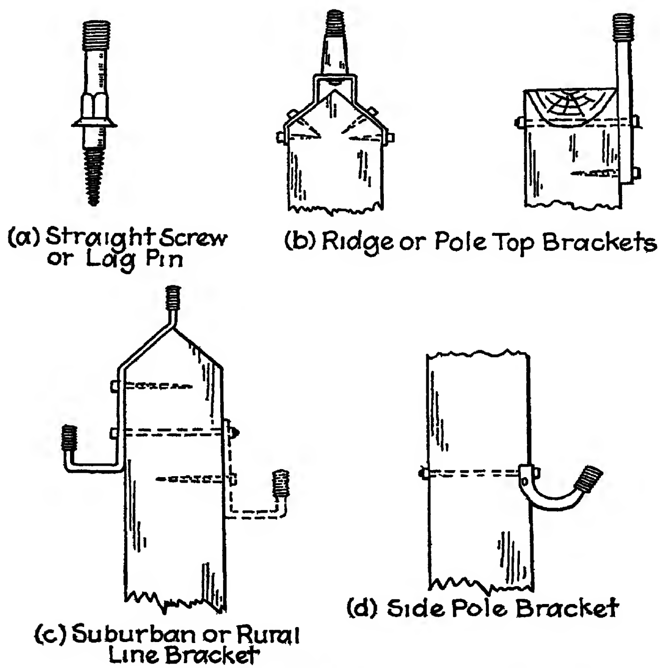


FIG. 211.—Miscellaneous brackets.

etc. It is evident that one pin would not be strong enough for such a loading. It is necessary to use two pins for even the lighter wires and for the heavier, even two pins are far from adequate. A dead-end construction using strain insulators is necessary for No. 0 and larger and some companies prefer to use such construction for all sizes.

It should be emphasized again that the use of steel pins does not necessarily add strength to the construction beyond what would be obtained with wooden pins. The steel pin may have other advantages but, unless properly designed for strength it may be considerably weaker than it might first appear. Tests

on a number of such pins have shown that by no means all such pins are sufficient to support 700-lb. pull on the insulator This is especially true of some of the special types shown below, such as ridge brackets, etc A test on any such pins which are to be used is recommended

Special Pins and Brackets.—A vast number of special pins and brackets for different purposes (mostly made of steel) are offered by the manufacturers Some of the most commonly used of these are shown on Fig. 211.

The straight screw or lag pin (Fig 211(*a*)) is used for installation on the side of poles or cross-arms, usually for the purpose of supporting vertical training wires

The pole top or ridge bracket, Fig 211 (*b*), is for supporting a wire on the top of the pole—usually used for the middle wire of a three-wire circuit when it is desired to have a symmetrical arrangement of wires

The suburban or rural line bracket, Fig. 211 (*c*), is mostly used for 2,300-volt primaries on rural lines, etc Where the circuit is a branch from a 4,000-volt four-wire circuit, the lower wire will be grounded and may also serve as the neutral for the secondary, a secondary rack being used in combination with this bracket where secondary is installed. A three-wire line may be run with an additional bracket as indicated by the broken lines

Secondary racks are sometimes in the form of the side-pole bracket, Fig 211 (*d*), in two- or three-pin types, but are usually of a different form as discussed in Chap. XVIII

CHAPTER XX

INSULATORS

It is obvious that all distribution conductors must be insulated in some manner from other conductors of the same and of other circuits, and also from ground. Since the supports used for overhead lines are usually more or less conductive, this requires that the wires be insulated from the supports. Ordinarily, the conductors used are either bare wires or have a so-called "weather-proof-braid" covering (rubber-insulated conductors are not often used, except in special cases). This covering is not a dependable insulation, except perhaps at the lower range of voltages and then only when comparatively new. Hence, at the supports, the conductors must be carried on insulators which will be effective for the voltage used. Insulation of the wires between supports is obtained by physical separation. Of course, multiple-conductor cables have some use in overhead work and in these, and in underground cables, the conductors (either single- or multiple-conductor cables) are effectively insulated for their whole length. This chapter, however, is intended to deal especially with the insulators used for insulating open-wire overhead lines, which are by far the most common type of distribution circuit.

Practically the only materials used for this kind of insulators are glass and porcelain.

Glass.—Glass is an effective insulating material and glass insulators are widely used especially for the lower voltages. Ordinary glass is more susceptible to breakage due to shock, mechanical stresses, and temperature changes than porcelain. For secondaries, a cracked insulator is not likely to be a serious matter and for such circuits at least the glass insulator is a very satisfactory type. Insulators are available, made of refractory glass (Pyrex for example), which overcome the difficulties mentioned to a considerable extent and are hence more suitable for the higher voltages.

Porcelain.—Porcelain is made in two general grades, called "wet process" and "dry process." The difference in manufac-

ture is more or less indicated by the designations *wet* and *dry*, the wet-process porcelain being molded directly from the wet clay mixture, while in the dry process the clay is partially dried, reground to a damp powder, and pressed into shape in steel molds. The dry process is cheaper than the wet and is better adapted to making the more intricate shapes. It has the disadvantage, however, of producing a poorer porcelain, one which is more or less porous, and which has less mechanical and electrical strength than wet-process porcelain. Probably, the least desirable feature of dry-process insulators is that they are quite likely to puncture under electrical stress rather than flashing over, while a well-made wet-process insulator should flash over before it punctures. A dry-process insulator, therefore, might appear sound and yet be punctured, while a wet-process insulator would be more likely to be shattered, or at least cracked, if damaged at all. It is therefore advisable to use only wet-process insulators where the insulating value of the insulator is important to the safety of workmen or the continuity of service. There are certain insulators, however, such as those used for secondary racks (knob type) or for service brackets of some types, which are of more or less peculiar shape and which are best adapted to manufacture by the dry process. In the examples mentioned, secondary voltage only is applied and the function of the insulator is usually not so important as it is with primary voltages, nor are the voltage stresses likely to be so high. Dry-process insulators have given good service in such cases.

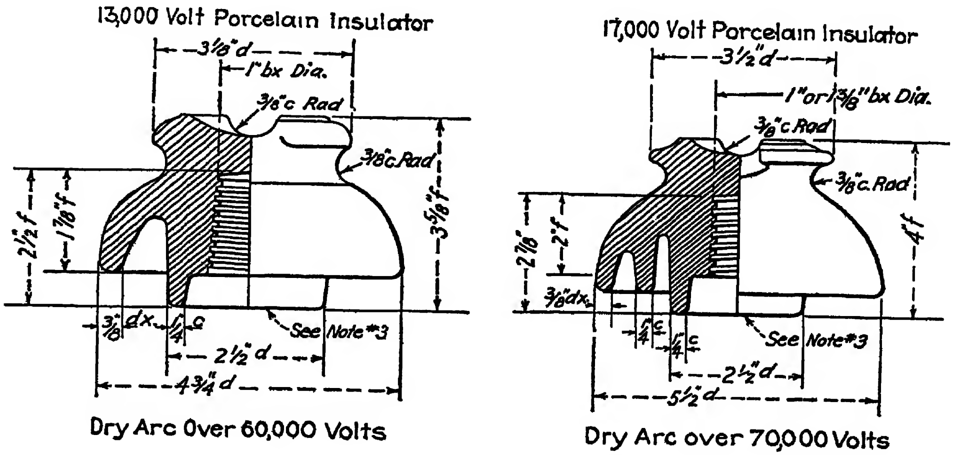
It should not be assumed that all porcelains of either class are of the same quality. There are wide differences in methods of handling the clay, mixing, firing, etc., which affect the finished product of either of the two types. Some dry-process porcelain is probably of better quality than some wet process. Electrical and mechanical tests on samples of the finished pieces will indicate serious weakness and are to be recommended as an aid in judging quality.

Types of Insulators.—The types of insulators most commonly used are described briefly below and illustrations of the most generally accepted designs given:

Pin-type Insulators.—These are used to support overhead line conductors, being mounted on the pins described in Chap. XIX.

Typical insulators for voltages of the order of 13,200 volts are shown in Fig. 212. Four porcelain insulators for use with voltages

up to 6,600 volts are shown on Fig. 213. Figure 213 (*a*) is a type which has been quite largely used in the past for voltages of 2,300 and 4,600 but which is being displaced in many places by other types which are stronger mechanically. Figure 213 (*b*) is a so-called "National Electrical Light Association suggested standard." It has the advantage of mechanical strength and grooves of large diameter which will accommodate conductors



Allowable Variation		
	Over	Under
a	1/64"	1/64"
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"
bx	1/32	0"
dx	1/8"	0"

—*Notes*—

Nº 1 - Minimum thickness of Wall surrounding threaded section 3/8"

Nº 2 4 Threads per inch tapering 1/16" in diameter to 1 inch in length

Nº 3 This edge of Insulator may be unglazed

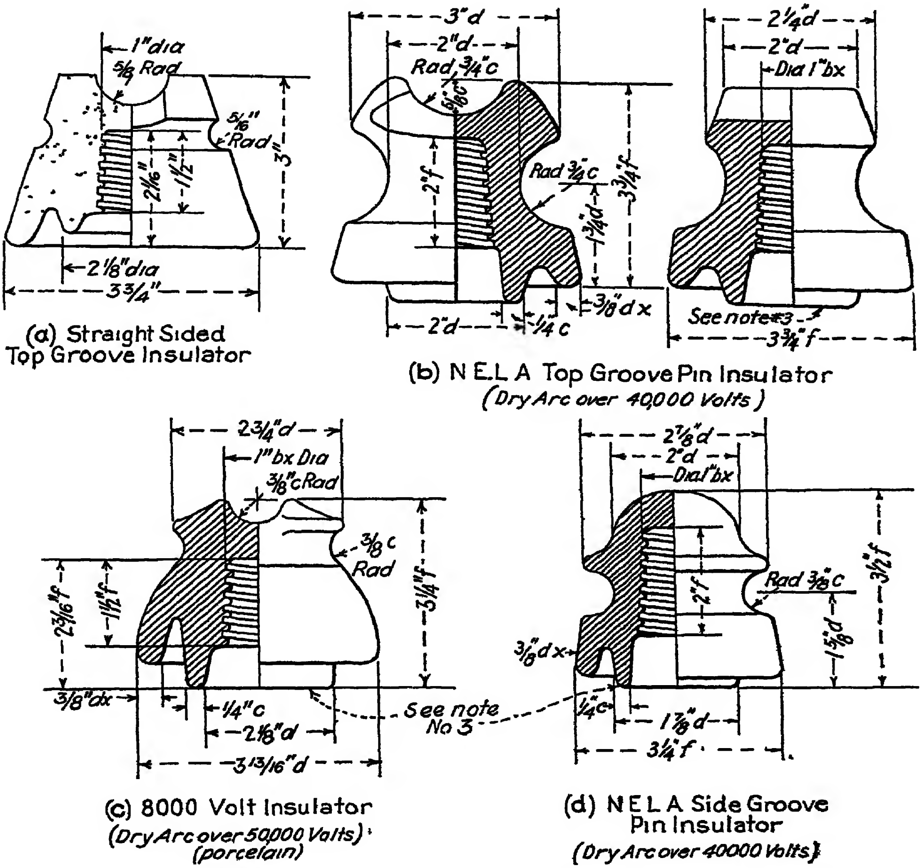
Material	*Finish*
Porcelain	*Brown*
Wet Process	*Glazed*

FIG. 212.—Insulators for voltages of the order of 13,200 volts.

up to very large sizes. Figure 213 (*c*) is another type which has large use. It is compact and has good mechanical strength. Its grooves are smaller than those of Fig. 213 (*b*) but will accommodate a No. 0000 T.B.W.P. wire. Figure 213 (*d*) is another National Electric Light Association suggested standard. It has no top groove and hence is not so adaptable to different conditions as are the other designs.

Several designs of standard glass insulators are shown on Fig. 214. A side-groove insulator is illustrated in Fig. 214 (*a*). This is suitable for wires up to No. 0000. For larger wires a

top-groove design is advisable in any case and such a design is given in Fig. 214 (*b*).



ALOWABLE VARIATIONS		
	Over	Under
a	1/64"	1/64"
c	1/64"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"
bx	1/32"	0"
dx	1/8"	0"

NOTES

1 - *Minimum Thickness of Wall Surrounding Threaded Section 3/8 Inch*

2 - *4 Threads per Inch Tapering 1/16 Inch in dia to 1 Inch in Length.*

3 - *This edge of Insulator may be unglazed*

MATERIAL	FINISH
Porcelain Wet Process	Brown Glazed

FIG 213.—Insulators for voltages up to 6,600 volts.

There are insulators of many other designs in use but those given above are representative and probably are the ones which have the greatest general use. A standardization on as few types

as possible is of course desirable, not only for an individual company but also for the country as a whole.

Guy Insulators.—The Safety Code stipulates that each guy which is attached to a pole or structure carrying any supply conductors of more than 300 volts to ground and not more than 15,000 volts between conductors or any guy which is exposed

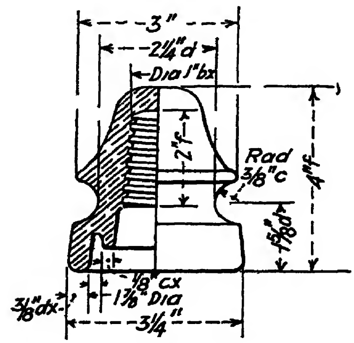
—NOTES—

1—Minimum thickness of Wall surrounding threaded section 3/8 in

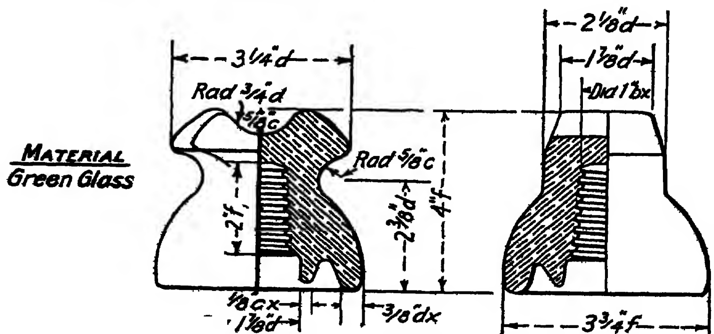
2—4 Threads per inch tapering 1/16 in in dia, to 1 in in length

3—Insulator may be made with or without Drip Points

ALLOWABLE VARIATIONS		
	Over	Under
a	1/64"	1/64"
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"
bx	1/32"	0"
cx	1/16"	0"
dx	1/8"	0"



(a) Side Groove Pin Insulator

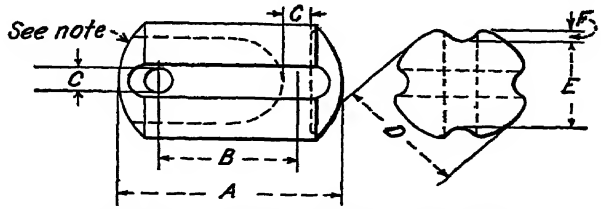


(b) Top Groove Pin Insulator

FIG. 214.—Glass insulators.

to such voltages, shall have an insulator in it. In many cases it is advisable to have more than one insulator in the guy to guard against possible accidents in case wires above sag down or break, or in case the guy breaks and swings into line conductors. Conditions of the case will govern the location of such insulators, the Safety Code merely specifying that the first insulator be from 8 to 10 ft. above ground and that the lowest one of two or more shall not be within 8 ft. of the ground.

On distribution lines, the most commonly used insulator for guys is the interlocking strain-ball type illustrated in Fig. 215. With such an insulator, the porcelain may break without having



(a) N E L A. Guy Strain Insulator

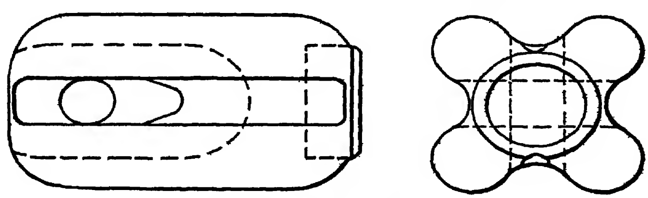
Trade No	A	B	C	D	E	F	Strength in Compression
502	3¼"f	1¾"f	7/16"c	2½"d	1¾"f	5/16"c	10,000 lbs
504	3¾"f	2¼"f	9/16"c	2⅞"d	2⅛"f	3/8"c	12,000 "
506	5¼"f	3⅛"f	¾"c	3⅜"d	2⅜"f	½"c	15,000 "

Allowable Variations		
	Over	Under
c	1/16"	1/16"
d	1/8"	1/8"
f	1/4"	1/4"

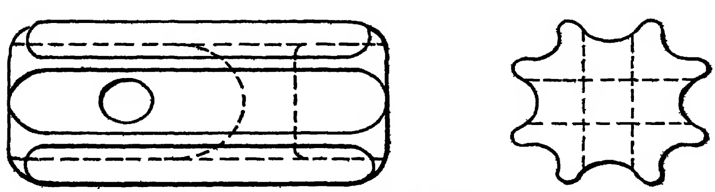
MATERIAL
Porcelain Wet Process

FINISH
Brown Glazed

NOTE
One end of Insulator may be unglazed



(b) Alternate Shape



(c) Multifin Shape

FIG 215.—Guy insulators (interlocking).

the guy part. Dry-process porcelain was formerly used to a large extent for such insulators but, for the reason given above in discussing dry- and wet-process porcelain, the tendency is now very strongly toward wet-process porcelain for this purpose.

It is not uncommon to find dry-process insulators, which appear to be sound on the exterior, to have punctures, due probably to lightning discharges. Such an insulator is a menace rather than a protection Three general types of guy insulators are shown, Fig. 215 (*a*) being a National Electric Light Association suggested standard which follows very closely the old dry-process design. Figure 215 (*b*), a somewhat different shape but not essentially different in principle or characteristics, is preferred by some. Figure 215 (*c*) is another type of considerably different cross-section. In general, it has a greater leakage distance than Fig. 215 (*a*) on account of the fins and may have higher flashover but is more costly to manufacture. All of these designs are made in several sizes to accommodate different sizes of guys. The three sizes are indicated for the National Electric Light Association standard.

Strain Insulators.—As was brought out in Chap. XIX in discussing the strength of pins, it is good practice to dead end the larger sizes of conductors in some form of strain insulator rather than on pin-type insulators. Some companies make a practice of dead ending all sizes of conductors in such a manner. There are several types of insulators used for this purpose. The strain-ball type described above for guy insulation is quite commonly used for low-voltage circuits (secondaries, etc.). These insulators are usually not so well adapted to higher voltages (2,200 volts or more) however, since the flashover value and the leakage distance, especially the latter, are likely to be considerably less than for some of the other types. In Fig. 216 three designs of disc insulators which are used for this purpose are illustrated. Figure 216 (*a*) is the Hewlett type. This is an interlocking insulator on somewhat the same principle as the strain ball but with much greater leakage distance. The hole is curved and hence is not well adapted to hold the larger wires by having them passed directly through it, but may be so adapted by the use of special hardware, the conductor being either clamped or served around a separate thimble. Figure 216 (*b*) is what is sometimes called the "pig-liver type." It is similar in principle to the Hewlett but has large holes running straight through from side to side, making it possible to serve large conductors directly through the insulator. Figure 216 (*c*) is a cap-and-pin type, the pin being cemented into and the cap cemented around the insulator. It is not interlocking. This is similar

to the design commonly used for suspension strings for supporting high-voltage transmission conductors. The Hewlett and the cap-and-pin types come in several sizes from 5 to 10 in. in diameter. Special hardware, in the form of clevises, links, hooks, thimbles, clamps, etc., is offered for use in attaching the insulators to the wire and to the support. These will not be described in detail. Care should be observed, however, in selecting such

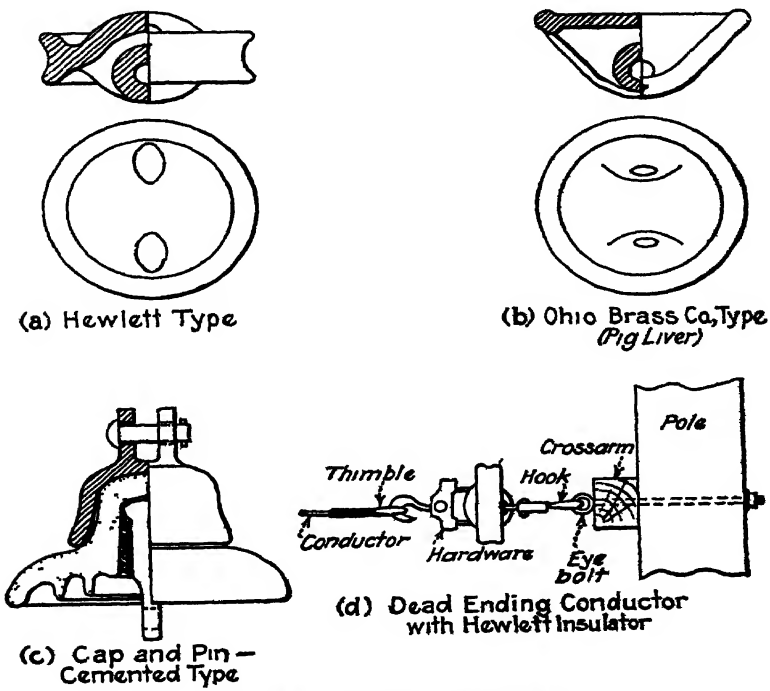


FIG 216.—Disc strain insulators.

hardware and in selecting the insulator itself that the assembly used has sufficient mechanical strength to withstand the probable load which may be imposed by the conductor under the most severe conditions assumed, and with a reasonable factor of safety. Figure 216 (*d*) illustrates the use of a Hewlett insulator in dead ending a conductor showing special hardware. The make-up for the other types is not greatly different.

Spools.—The spool-type of secondary rack was described in Chap. XVIII. The spool insulators for such racks are quite well standardized in design. Figure 217 shows the National Electric Light Association suggested standard which is quite

generally followed. These spools are commonly made of dry-process porcelain but are also available in wet-process porcelain, the latter having somewhat greater electrical and mechanical strength.

Special Insulators.—There are of course numberless special designs of insulators for special uses or peculiar to individual manufacturers, which cannot be said to have been at all standardized, *i.e.*, they are not generally accepted and made by all manufacturers. Among these may be classed the knobs for knob-type secondary racks (see Chap. XVIII), insulators for

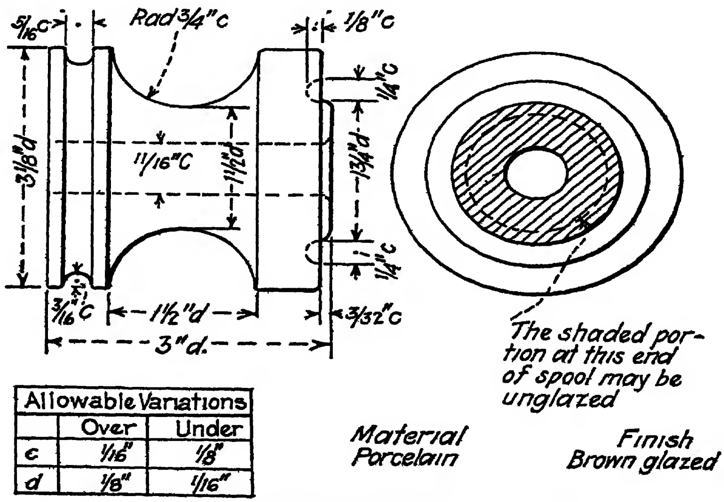


FIG. 217.—Spool for secondary racks.

service brackets (see Chap. XXI), various bushings, supports, etc., used in connection with fuse boxes, disconnecting switches, transformers, etc., and the like. One insulator which may be considered as special although it may be quite useful in some cases in the so-called "service insulator," one type of which is illustrated in Fig. 218. This allows both line and service wires to be tied to the same insulator.

Test Voltages.—The practical insulating value of any insulator may be quite well gauged by two qualities, its flashover value and its leakage distance. The two may be more or less related in some insulators but not necessarily so, since the leakage path may be considerably longer in one insulator than another without correspondingly increasing the flashover. The leakage distance

becomes important after the insulator has been in service for some time and has become dirty, the flashover being a good measure of insulating value for clean insulators.

Specific ratios between operating voltage and flashover for good design are rather hard to establish as there are other affecting factors, such as local atmospheric conditions, mechanical strength, type of circuit, type of supports, etc.

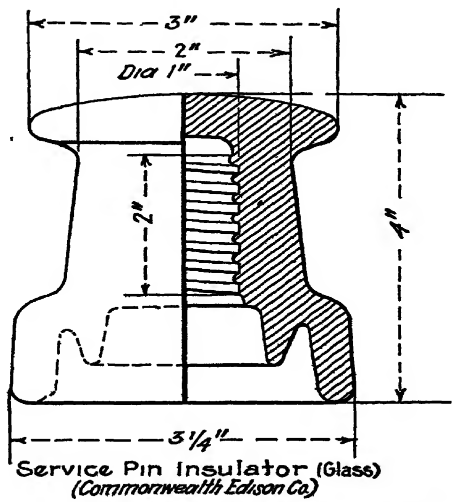


Fig. 218.—One type of service insulator.

The Safety Code stipulates the following minimum values for flashover, tests to be made according to A.I.E.E. specifications.

Nominal Line Voltage	Minimum Test Dry Flashover Voltage of Insulators
750	5,000
2,300	20,000
4,000	30,000
6,600	40,000
11,000	50,000
22,000	75,000

These should be considered as *minimum* values. It is probable that in most cases, in practice, the insulators used will exceed these requirements somewhat. The insulators shown on Fig. 213 have, as a rule, flashovers of from 40,000 to 50,000 volts

and are quite generally used on circuits of 2,300, 4,000, 4,600, and 6,600 volts. Where metal supports (poles and cross-arms) are used it is well to use somewhat better insulation than with wood construction, if the insulators are anywhere near the minimum requirements given above. With ungrounded circuits, the insulation should be sufficient for full line-to-line voltage to ground, whereas with a circuit with *thoroughly grounded* neutral, the voltage to ground is held to $\frac{\text{line voltage}}{\sqrt{3}}$. This is not true of all grounded neutral systems, however, as on some it may be possible for full line-voltage to occur to ground. In localities subject to severe smoke, salt fog, dust, chemical fumes, etc., it is often desirable to use insulators of considerably higher flashover than the minimum or at least to provide especially long leakage distance.

CHAPTER XXI

SERVICES

The term "service" is here used to designate the service branch or loop which connects the customer to the general distribution mains.

Although it might appear more logical to include a discussion of services in the chapter on "Conductors," it is introduced here in a separate chapter because a considerable part of the points brought out will concern the supports or attachments and hence is closely related to the preceding chapters.

Services may sometimes be considered as a rather insignificant part of the distribution system, since the individual service is ordinarily a comparatively short run of relatively small conductor. It must be remembered, however, that, while the distribution mains serve a large number of customers, there is a service to *each* customer, and in the aggregate these comprise a considerable portion of the system. Economy in design and installation of services is therefore well worth attention. Furthermore, the service is the part of the system closest to the customer and is usually wholly or in part on his premises. A neat, workmanlike service is therefore an asset in its favorable impression on the customer.

Types of Services.—Services may be either underground or overhead. Where the distribution mains are underground, the services will naturally be underground also. Where the mains are overhead, customers sometimes prefer the service wires to be underground to avoid what is deemed the unsightliness of overhead wires swinging across their property. From the point of view of the power company, such underground services are usually not considered desirable. Unless installed in conduit or otherwise securely protected, the cable is subject to damage by being dug up or having stakes, etc., driven into it. If it fails, the trouble is somewhat difficult to locate and may involve digging up a lawn to reach and repair it. Even if in conduit, the replacement of the cable in case of trouble is likely to take considerable

time. The trouble and delay in restoring service is very often charged against the power company by the customer, who forgets that the underground service was installed at his especial request. It must be recognized that underground services are justified under certain conditions.

Underground services are sometimes run in conduit but, where tapped from overhead lines, the conduit is more often omitted to reduce the cost. In such cases the cable should be "armored" or protected from damage as far as possible in some other manner Lead-sheathed, rubber-insulated cable has been universally used for this purpose until recently, when several forms of braid-covered waterproof cable have been introduced. These offer the advantages of lightness and less cost and elimination of the terminal pothead on the pole, which must be used with a lead-sheathed cable. The user should be assured that such a cable is properly made to resist the entrance of moisture, however, or its use may well be a fertile source of trouble as time goes on.

Overhead services may be run with either "open-wire" construction or multiple-conductor, braid-covered cable. Open-wire construction, with the separate conductors held apart on separate insulators, allows the use of cheaper wire (weatherproof braid-covered wire is commonly used), makes the detection of trouble on the service wires, if such should occur, somewhat easier, and allows the addition of a third wire to a two-wire service without replacing the other wires. Multiple-conductor cable ("duplex" or "triplex" as it is sometimes called) is considered by many to make a much neater appearance and, in congested districts especially, this advantage may be of sufficient importance to offset the other advantages of open wire. Multiple-conductor service cable usually is made with two or three rubber-insulated wires enclosed in a braid sheath (usually double), or it may be simply two or three insulated wires twisted together.

Size of Conductor.—The size of conductor to be used for any service will, of course, depend very largely on the load to be served. For mechanical strength, no smaller than a No. 8 (A.W.G.) copper should be used in heavy-loading districts. The Safety Code specifies a minimum of No. 10 copper for voltages less the 750 volts and spans less than 150 ft. For longer spans or higher voltage, the requirements are practically the same as for line conductors (see Chap. XXII). For the larger services, *i.e.*, those requiring the larger sizes of conductors, it

will often be found that a considerably smaller size may be used than is brought out of the building by the customer. This is because the interior wiring is likely to be sized according to total connected load, or a large percentage of it at least, not recognizing to the fullest extent the probable demand factors. It is unnecessary for the outside service wires to be any larger than is consistent with economy and with allowable voltage drop, based on the actual load to be carried as determined by test or experience with similar loads. Data on demand factors which have been found with various types of loads is given in Chap. IV.

TABLE XIX.—CONDUCTOR SIZES FOR SERVICES

Single-phase Services:	
Single residence, lighting, 4 kv-a. or less (connected) (unless including a device drawing 2 kv-a. or more)	2 No. 8
Business buildings, lighting, 2 kv-a. or less (connected)	2 No. 8
Residence lighting, over 4 kv-a. and less than 6 kv-a (connected) or including a device drawing 2 kv-a. or more	3 No. 8
Business lighting, over 2 kv-a. and less than 6 kv-a (connected)	3 No. 8
Lighting load, over 6 kv-a. (connected)	3 No. 6
Electric Ranges:	
2 plates, both less than 660 watts	3 No. 8
2 plates, one greater than 660 watts	3 No. 6
3 or more plates	3 No. 6
Motor:	
½ to 5 hp	3 No. 4
5 to 15 hp (third [neutral] wire not required for 230 volt motor only)	3 No. 2
Large residences, apartments, stores, etc. with heavy load:	
10 to 15 kv-a. (connected)	3 No. 4
15 to 25 kv-a. (connected)	3 No. 2
25 to 50 kv-a. (connected)	3 No. 0
50 to 100 kv-a. (connected)	3 No. 0000
100 to 150 kv-a. (connected)	3 350 M
150 to 200 kv-a. (connected)	3 500 M
Over 200 kv-a. (connected)	3 750 M
Three-phase Services:	
One 5-hp. motor or less for occasional use	3 No. 8
Up to 10 kv-a. (actual load) not over 20 hp. (connected)	3 No. 6
10 to 15 kv-a. (actual load) not over 35 hp. (connected)	3 No. 4
15 to 25 kv-a. (actual load) not over 55 hp. (connected)	3 No 2
25 to 50 kv-a. (actual load) not over 110 hp. (connected)	3 No. 0
50 to 100 kv-a. (actual load) not over 225 hp. (connected)	3 No. 0000
100 to 150 kv-a. (actual load) not over 350 hp. (connected)	3 350 M
150 to 200 kv-a. (actual load) not over 500 hp. (connected)	3 500 M
Over 200 kv-a. (actual load)	3 750 M

Table XIX gives a list of suggested sizes for services for various loads. These are perhaps not universally applicable but have been determined as the result of experience and also studies of voltage drops and economy for average conditions on one system.

Service wires occur usually in relatively short spans and are likely to be strung quite slack compared with line wires. This is good practice in order to reduce the stress on the point of attachment to the building as much as possible, since a secure anchorage to the building is not always obtainable. A maximum limit of 100 ft. for the span (without intermediate support) is desirable but not always practicable or necessary. A good ready rule in regard to sags, for spans up to 100 ft. at least, is to make the sag in a service twice as much as that in a normal span of line wire of the same length. The Safety Code stipulates, for voltages less than 750 volts, minimum sags of:

12 in for spans 100 ft. or less.
18 in. for spans 100 to 125 ft.
27 in. for spans 125 to 150 ft.
Grade C for spans exceeding 150 ft.

These sags are less than are specified for line wire in similar spans and while permissible as minimums on account of the low voltage and the more or less shielded location of the span, cannot be recommended as the best for average practice, especially in heavy-loading districts, except possibly for the longer spans, where any considerable increase might not be practicable. It quite often happens that the service wire is higher at the pole end than it is at the building and, in such a case, the actual effective sag is somewhat difficult for the construction man to estimate. The tendency would usually be to have it more than the above minimums.

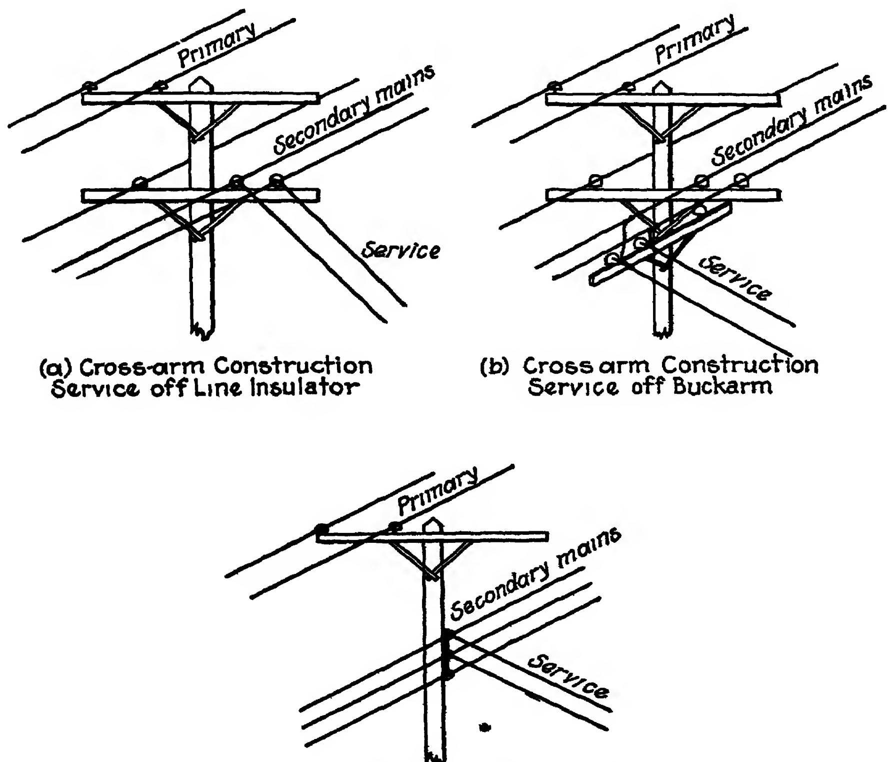
Soft-drawn copper is usually desirable for service wires since it is easier to work with in making connections to the line wires and service wiring and is not likely to be overstressed in the short spans if ample sags are allowed.

Attachment at Pole.—The service is supported or anchored at the pole end in several different ways:

1. With the secondary mains carried on cross-arms, when services are few and of small-sized wire, services are quite often held on the same insulators with the line wire. This is an

economical method but not well adapted to more than a very few services per pole, see Fig. 219(*a*).

2. Where the services are numerous or of large size, it is better, with cross-arm construction, to install a separate buck arm at right angles to the line arm and take off all services from this. This method is adaptable to almost any number of services and



(a) Cross-arm Construction Service off Line Insulator

(b) Cross arm Construction Service off Buckarm

(c) Secondary Rack Construction

FIG 219.—Attachment of services at pole.

leaves the line arm clear, which is a considerable advantage in case it becomes necessary to replace the wire of the secondary main. Connection of services to secondary main may be made with a single set of jumpers from line arm to buck arm, see Fig. 219(*b*)

3. Brackets of various kinds are sometimes used, attached to pole or cross-arms, to afford anchorage for the services and clearance past other wires. In general, such construction is not of

any particular advantage over the buck-arm method and is likely to be far less sightly.

4. Where secondary racks are used for the mains, the usual practice is to attach the services to the same insulator with the

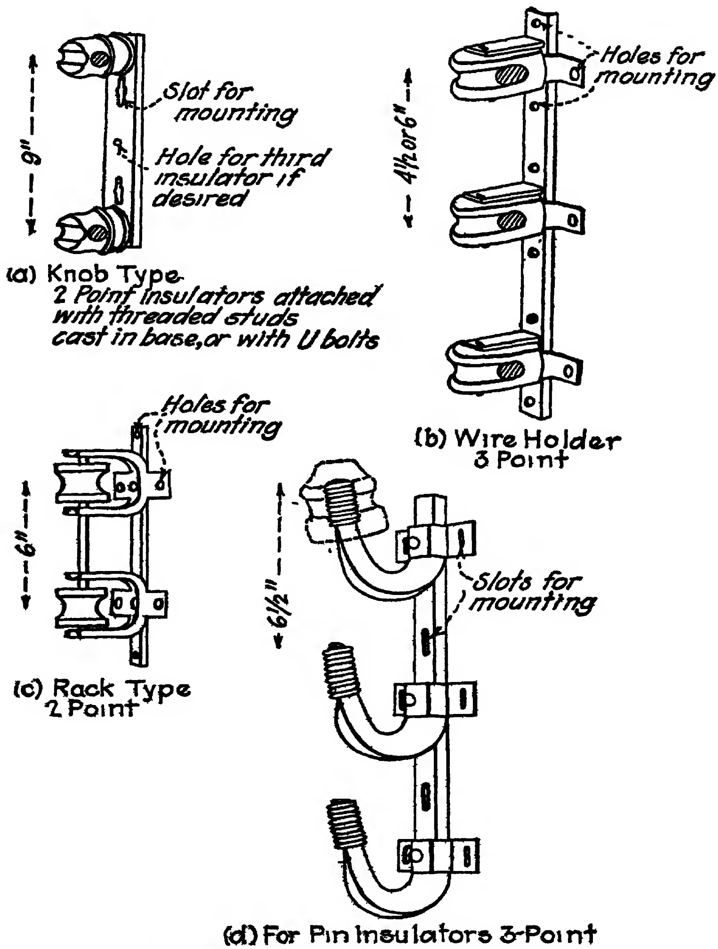


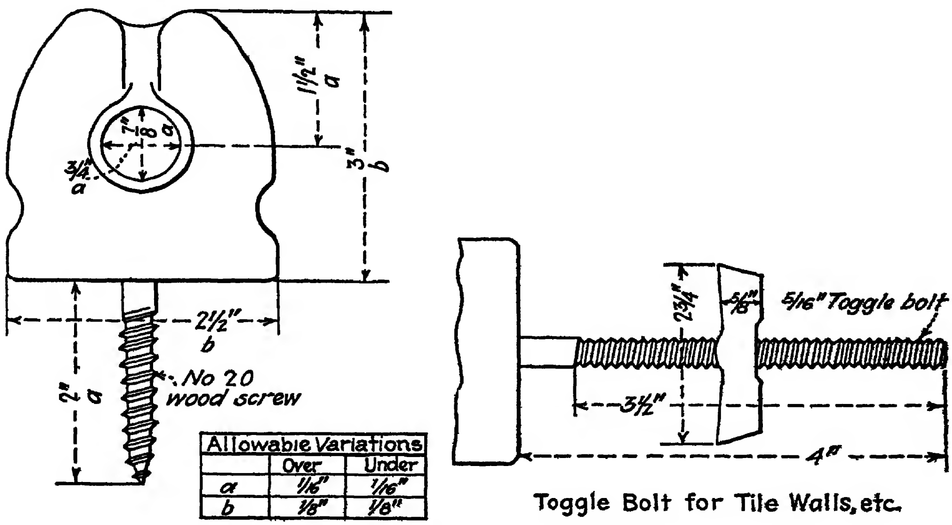
Fig. 220.—Multipoint service bracket.

main, see Fig. 219(*c*). This is further illustrated in Chap. XVIII. It is the best of the methods indicated, from the standpoint of simplicity and strength.

5. Where multiple-conductor cable is used, the conductors may be separated and anchored separately in any of the ways shown,

or special brackets may be used for holding the whole cable. Such a one is illustrated with the house brackets. It may be used at the pole as well.

Attachment at Building.—The service is usually held at the customer's building wall in some form of a service bracket. For the lighter wires, these brackets are made in two general types, the multipoint (two or three point) and the single point. The former consists of a steel back of some sort, often a pressed-steel channel, with either two or three insulators, as required, mounted



Allowable Variations		
	Over	Under
a	1/16"	1/16"
b	1/8"	1/8"

Fig. 221.—Single-point service bracket.

upon it. Figure 220 illustrates several varieties of such brackets. While these were formerly used to a large extent, they have been supplanted in many places by the one-point bracket on account of the latter's adaptability to varied conditions. Where the multipoint bracket is used, usually both two-point and three-point brackets are carried in stock, as well as extra insulators and screws, anchor bolts, etc., for attaching the brackets to the walls.

The one-point bracket is commonly used in the form shown in Fig. 221, *i.e.*, consisting of a single piece of porcelain with a wood-screw fixed in a socket in its base. Single-point brackets are also obtainable in similar designs to those shown in Fig. 220 or multipoint brackets. These brackets are comparatively

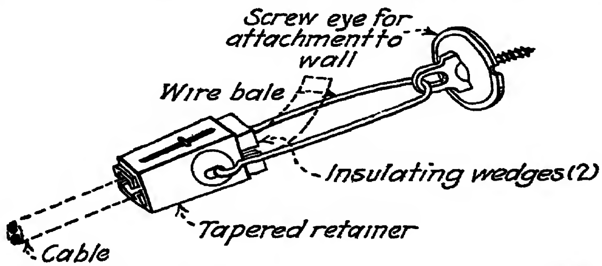
strong, if properly designed, are convenient to use, and eliminate the necessity for carrying a multiplicity of parts in stock—either two-point or three-point services may be run by using two or three brackets, and the screw for attachment to the wall is self-contained. Several points in the design of such a bracket are worthy of careful attention. The porcelain should be strong enough to stand not only the probable wire load when it is in place, but also a reasonable amount of rough handling in the warehouse and on the service wagon. The porcelain is usually made by the dry process on account of its more or less intricate shape. This is obtainable of a quality which has very good mechanical strength and is quite satisfactory for this purpose. Another feature which may occasion difficulty is the type and finish of the screw threads. A sharp, clean thread makes for ease of installation in all kinds of anchorages, while a thick, rough thread will cause delays and breakage of porcelain. Too large a screw is also likely to be a detriment for the same reasons. A sharp wood-screw thread of about size No. 20 or possibly No. 22 is preferable. A hot-dip galvanizing finish, while a good rust preventive, is likely to fill up the threads to some extent and leave a relatively rough surface. Cadmium plating or sheradizing have much less effect on the threads and are preferable for this purpose. The screw should have a head which will prevent it from turning when secured in its socket, that is, it should be square or be provided with fins of some sort. The screw is usually fastened in the socket by filling in around it with either lead alloy or cement. The latter is somewhat cheaper but trouble is likely to be experienced with some types of cement in their not weathering well or in their promoting corrosion of the screw. The socket should be recessed or otherwise prepared to lock the screw in place. These brackets are made in several sizes. The one illustrated in Fig. 221 is a medium size which answers well for most general purposes.

Heavy-service wires (No. 0 and larger) usually require a more substantial support than the ordinary service bracket. A secondary rack is suitable for this purpose. A construction making use of strain insulators, similar to that illustrated in Chap. XXII for dead-ending secondaries, Fig. 239, is also quite often used, especially for the very large sizes.

Multiple-conductor cable services offer somewhat of a problem since the cable is too rigid to serve through an ordinary bracket in the way single wire is handled. The conductors may be

separated and each one anchored or a special bracket for holding the whole cable may be used. Figure 222 illustrates such a bracket which has been recently brought out. Its action depends on holding the cable between two bakelite wedges slipped into a metal sleeve.

Care should be taken that the attachment of the bracket to the building wall is secure enough to develop the strength of the bracket to as great a degree as is practicable. Multipoint brackets are attached to wooden structures with wooden screws or small lag screws (¼ in.) and to masonry walls with anchor



Service Bracket for Multiple Conductor Cables
(Hubbard & Co.)

FIG. 222.—Bracket for multiple conductor cable.

bolts. With the one-point bracket, an expansion shield, usually of lead, is ordinarily used, placed in a hole drilled in the wall and the bracket screwed into it. Anchor bolts and anchor shields are made in various types and sizes and some care is warranted in selecting, by test if possible, one which is of the proper size and strength for the purpose. Veneer brick walls are likely to present somewhat of a problem since the masonry is usually not strong enough to adequately hold the bracket with an expansion shield and too thick to allow the ordinary screw to pass through it into the frame. Long screws are sometimes used for this purpose but are not entirely satisfactory in all cases. A good solution of the problem of attachment to any type of masonry wall is to require the customer, when the building is erected, to furnish a wooden surface, either attached to or built into the wall at a proper location and properly anchored to it, to which service brackets may be attached. The wood-screw bracket is then sufficient for all services.

The bracket should be placed on the building within easy reaching distance (2 or 3 ft) of the point to which the customer's wiring

will be brought and that point should be high enough above grade to give the service wires proper clearance (at least 10 ft.). Where it is necessary to run the wires along the wall for some distance to reach the entrance point, they should be supported on additional brackets placed not over 10 ft. apart, with the last one near the entrance point. Figure 223 illustrates service wires on a building.

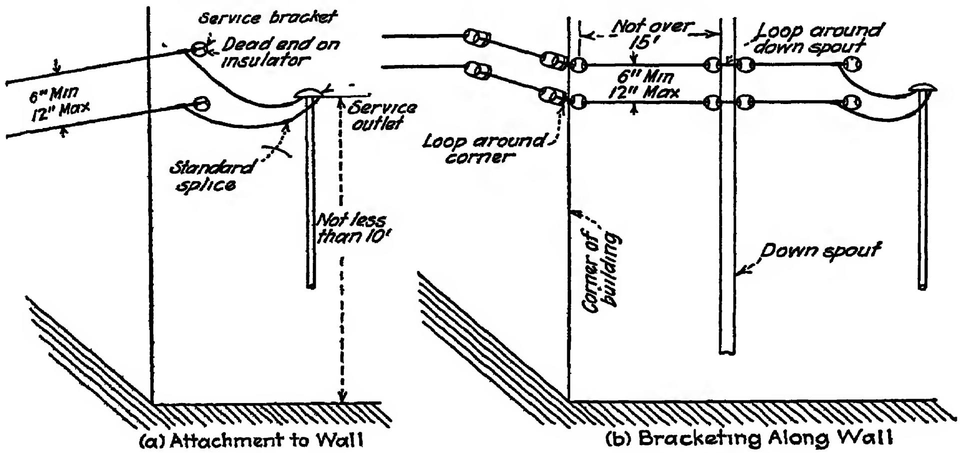


FIG. 223.—Attachment of service wires to buildings.

Strength of Brackets.—The strength necessary in a service bracket and its attachment to the wall depends of course on the size of conductor, its maximum wind and ice loading, and its sag. A practical maximum limit is somewhere near the elastic limit of the conductor, as beyond that point the conductor might stretch and relieve the tension. For soft-drawn copper this varies from about 250 lb. for No. 8, to about 1,000 lb. for No. 2, 3,000 lb. for No. 0000, etc. If extra sag is allowed in the service however, as was suggested, these stresses will not be reached, the proportion which may be expected depending on the increase in sag used over the normal sag based on the elastic limit as an ultimate tension.

From quite a number of tests made on one-point service brackets of the type illustrated in Fig. 221, it may be assumed that a strength of 1,500 lb. in direct pull is not unreasonable for a well-made bracket, some holding 2,000 lb. or more before breaking. The porcelain should break before the screw pulls out in a

proper design. The strength of the hold of the screw in the wood is likely to be the weak point of the construction when the bracket has this strength. Multipoint brackets of similar design have similar strength. With some of the other types of multipoint brackets, failure will take place in the steel back or framework or in the means of holding the insulator, rather than in the porcelain itself, and the strength in such cases will usually be less than that indicated above. For strength in a direction at right angles to the axis of the screw (dead weight or side pull) 500 lb. was found in the tests mentioned to be a reasonable requirement.

CHAPTER XXII

CONDUCTORS

The conductors on an overhead line are probably more subject to mechanical failure than any other part of the construction. This is due to two factors:

1. They are under electrical stress (voltage) between each other and to ground. Any breaking down of insulation, either by failure of other parts of the structure or by the coming together of the wires, will cause an electrical failure, which is very often accompanied by a burning of the conductors and their mechanical failure.

2. It is desirable to have a relatively small amount of sag in the wires in order to reduce the chance of their swinging together. The tension, however, is approximately in inverse proportion to the sag and hence, from that standpoint, a relatively large sag is desirable in order to minimize the stress. Trying to satisfy both these requirements usually results in a sag whihc will stress the conductor up to at least its elastic limit when the heaviest assumed loading is experienced, leaving relatively little margin for safety factor to provide for occasional unexpected large stresses.

When it is remembered that mechanical failure of a conductor results in complete interruption to the circuit, it is evident that careful attention to the mechanical design of this part of the structure is extremely important in order that the chances of mechanical failure be minimized as far as possible.

Conductor Materials.—The materials which are suitable for conductors and which are economically available are very limited in number. A brief discussion of those commonly considered will be given with special reference to their mechanical features.

Copper.—Copper is the most commonly used conductor material and in many ways is the most satisfactory for general purposes. Its conductivity is high and is used as a reference for that of other materials. It is easily handled being soft enough

to be readily "served" up and yet hard enough to be not unduly subject to injury. It may be spliced or joined effectively by simple serving and soldering. The disadvantage of copper for some types of lines lies in its relatively low-tensile strength. This limits its use to comparatively short spans with the smaller sizes of conductors. For urban distribution this disadvantage is usually not of much importance since the length of span is ordinarily governed by other factors such as location of streets and alleys, necessity for reaching customers conveniently, etc., rather than by conductor size. For rural lines, however, economy may often be realized by use of long spans, eliminating as many poles as possible, and a higher strength conductor may therefore prove of considerable advantage.

Copper wire is made in three standard degrees of hardness called "hard drawn," "medium hard drawn," and "soft drawn." *Hard-drawn copper* is the result of drawing the wire down to size without subjecting it to annealing. It is the strongest of the three grades as will be seen by reference to Table XX. At the same time it is harder to work with, *i.e.*, it is stiffer and cannot be served up or otherwise handled so readily. It is used where high strength is especially important but is not as generally employed for distribution lines as the medium hard drawn.

Medium-hard-drawn copper wire is made by drawing the wire nearly to size, annealing it, and then redrawing it to size, giving it a certain hardness but not as much as that of hard drawn. Its tensile strength is between that of soft drawn and hard drawn and is somewhat indeterminate, covering a wider range of values than that of either of the other grades. Its "workability" is also intermediate between that of soft-drawn and hard-drawn copper, which makes it well adapted for use on distribution lines where joints, taps, etc., are numerous. *Soft-drawn* copper wire is the result of annealing the wire after drawing. It is very flexible and easily worked but is also relatively low in tensile strength. Soft-drawn is not usually recommended for line conductors for that reason but is commonly used for service wires for which the span is usually short, the sag relatively large, and joints necessary at both ends of relatively short lengths. Soft-drawn copper is also used for tie wires. For underground cables, interior wiring, and other uses where mechanical strength is not a major requirement, soft-drawn copper is nearly always preferred on account of its flexibility.

Aluminum.—Aluminum wire is a competitor of copper for electrical conductors. Its conductivity is less than copper (about 63 per cent as great) but this is compensated for by the fact that aluminum is much lighter in weight than copper (about one-third as heavy). Hence, for conductors of the same conductivity, the aluminum will be only about one-half as heavy although being of somewhat larger diameter. Aluminum has the characteristic of being relatively low in tensile strength, its strength being about two-thirds that of soft-drawn copper. The breaking strengths of aluminum and soft-drawn copper conductors of equivalent conductivity are therefore practically equal. Aluminum is also considerably softer than copper and is subject to mechanical injuries in handling which materially affect its strength. These factors are unfavorable to the use of aluminum for line conductors, at least in the smaller sizes and in heavy-loading districts. In spite of the fact that the conductor itself is lighter than copper for equivalent conductivity, the additional ice and wind loads due to its larger diameter make the total resultant load, under maximum heavy-loading conditions, somewhat greater as a rule. Plain aluminum conductor, therefore, usually does not compare favorably with medium-hard or hard-drawn copper from the standpoint of mechanical strength.

Aluminum conductor with steel reinforcement is intended to remedy this deficiency. It is made with a central core of one or more strands of high-strength steel surrounded by strands of aluminum. The steel gives it mechanical strength and the aluminum, conductivity. The breaking strength of this conductor is about twice that of the equivalent conductor of plain aluminum. It is, therefore, considerably stronger than copper wire, even hard-drawn copper of equivalent conductivity. This makes it suitable for use in construction where mechanical strength is an especially important factor, such as where long spans are desirable. Steel reinforced aluminum or A.C.S.R. as it is called (aluminum cable steel reinforced) is quite commonly used for transmission lines, where on account of the topography of the route or in order to realize economy, long spans are necessary or desirable. In distribution work it is particularly applicable to lines in rural districts (farm lines) where spans are not limited in length to the extent which they are in urban territory, and where considerable economy can often be realized by the reduction in the cost of poles if spans of the order of 250 to 300

ft. are used. Copper wire in the smaller sizes is not suitable for such spans in heavy-loading districts but the high mechanical strength of A.C.S.R. allows its use, even in sizes as small as No. 4 (equivalent to No. 6 copper). Number 4 for example has an ultimate strength of 2,660 lb. as compared with 1,280 lb. for No. 6 hard-drawn copper.

The fact that A.C.S.R. is made of two different materials not homogeneously bound together, introduces certain difficulties into the problems connected with its use. The scrap value of salvaged material is reduced by the cost of separating the two metals. The tensile and elastic characteristics are composite, both materials contributing their own characteristics in proportion. This will be discussed somewhat further under the general characteristics of various materials given below.

Aluminum has the disadvantage, compared with copper, that it is very difficult to solder, a field job of soldering being almost out of the question. This is largely due to the very rapid formation of oxide on the surface of the freshly cleaned metal. When using aluminum or A.C.S.R. as a conductor, joints are made with either twisted sleeve connectors (for joining small conductors), special compression joints (for large conductors), or clamps (for taps). Where aluminum is joined to copper conductors special aluminum clamps with copper bushings should be used. Such joints are satisfactory electrically and probably no more difficult to make than the ordinary joints with copper when the special equipment is at hand. The facility with which copper may be joined and soldered without special equipment, however, is often a convenience, especially in an emergency.

Steel.—Steel wire is sometimes used as a conductor but not very commonly for electrical distribution, since its conductivity is relatively low (see Chap. XIV). It may be had in several grades, some of them of very high mechanical strength, and where mechanical strength is of primary importance and electrical conductivity only secondary, steel wire is suitable. It should, of course, be galvanized or otherwise protected from corrosion. Little consideration is given steel conductor in this chapter as it is felt that its field of usefulness as an electrical power conductor is relatively small.

Copper-covered Steel.—A composite conductor made with a core of high-grade steel surrounded by a layer of copper offers the advantages of high mechanical strength and fairly good

conductivity It is important that such conductors be manufactured in such a way that the material is homogeneous, *i.e.*, that the copper is securely and continuously welded to the steel. Copper-covered steel is made in two grades of conductivity, 30 and 40 per cent copper (referring to the percentage which the conductivity bears to the conductivity of hard-drawn copper wire of the same cross-section) and in two degrees of strength, determined by the grade of steel contained. Where used for distribution lines, the 40 per cent conductivity with the lower tensile strength steel is usually preferable, the higher strength being more commonly used for guys, messengers, and similar purposes. Copper-covered steel will be found a satisfactory material for long-span rural lines and the like, but where the electrical load is such that conductivity is relatively important it may be found that the size necessary on that account is out of proportion to the mechanical strength required. For example, for a conductivity equivalent to No. 6 copper, a 40 per cent copper-covered conductor must be No. 2, with a tensile strength of 4,000 lb., as compared with 1,280 lb. for hard-drawn copper, and 2,660 lb. for No. 4 A.C.S.R.

Copper-covered steel has the advantage that since its outer surface is of copper, it may be handled the same as copper wire in making joints, taps, etc. The heavy copper covering and homogeneous structure insures it against destructive corrosion in most cases.

Alloys.—Alloys of copper, such as various forms of brass and bronze, are sometimes used for conductors where higher mechanical strength is desired than is afforded by copper. They have the characteristic in general of having less conductivity than copper, the amount depending on their composition and method of manufacture. It is well known that certain alloys of copper, even when the material added is a relatively small percentage of the whole, have only a fraction of the conductivity of copper although the tensile strength is increased very considerably. Care should be used in employing such materials, therefore, to be sure that the alloy is such that the conductivity is not so reduced. Some of the alloy conductors on the market are claimed to have conductivities as high as 90 per cent of that of copper, obtained by certain heat-treating processes as well as by the composition. These alloys have the advantage of being sufficiently similar to copper to allow them to be handled like copper in making

TABLE XX.—CHARACTERISTICS OF CONDUCTOR MATERIALS (COMMERCIAL GRADES)

Material	Conductivity (pure copper, 100 per cent)	Weight		Ultimate strength, pounds per square inch*	Elastic limit, pounds per square inch	Modulus of Elasticity	Temperature coefficient of linear expansion	
		Pounds per cubic inch	Pounds per 1,000 ft per circular mil				Degrees Centigrade	Degrees Fahrenheit
Copper:								
Soft drawn . .	99 to 100	0.320	0.003027	36,000 to 40,000	18,000 to 20,000	12×10^6	17.1×10^{-6}	9.5×10^{-6}
Medium hard drawn	98 to 99.5	0.320	0.003027	42,000 to 60,000	23,000 to 33,000	14×10^6	17.1×10^{-6}	9.5×10^{-6}
Hard drawn ..	97 to 99	0.320	0.003027	49,000 to 67,000	30,000 to 35,000	16×10^6	17.1×10^{-6}	9.5×10^{-6}
Aluminum, plain	61	0.0967	0.000920	23,000 to 27,000	14,000 to 16,000	9×10^6	23.1×10^{-6}	12.8×10^{-6}
Aluminum, steel reinforced† (A C S R)	61	0.147	0.00139	44,000	31,000		19.1×10^{-6}	10.6×10^{-6}
Steel.	8.7	0.283	0.002671	45,000 to 189,000	23,000 to 112,000	29×10^6	11.8×10^{-6}	6.6×10^{-6}
Copper-covered steel, 30 per cent	29.25	0.298	0.00281	60,000 to 100,000		$16 \text{ to } 20 \times 10^6$	13.0×10^{-6}	7.2×10^{-6}
Copper-covered steel, 40 per cent.......	39	0.298	0.00281	60,000 to 100,000	. .	$16 \text{ to } 20 \times 10^6$	13.0×10^{-6}	7.2×10^{-6}
Copper alloy (Hitenso BB)‡.......	77 to 85	0.321	0.00303	70,000 to 85,000	42,000 to 51,000	16×10^6	17.1×10^{-6}	9.5×10^{-6}
Aluminum alloy (Aldrey)‡	52 to 53	0.0967	0.00092	40,000 to 47,000	.	93×10^6	23.0×10^{-6}	12.8×10^{-6}

* Strength varies somewhat with size. The larger values given are for small wire, the smaller for large wire of the order of No. 0000 solid (for copper). For stranded wire the strength is usually assumed to be about 90 per cent of the sum of the strengths of the individual strands.

† The values for A C S R depend on the proportion between steel and aluminum. Those given are approximate for 1 to 6 ratio.

‡ These are trade names of alloys for which the data was readily available. Others are in use also.

joints, etc., and to have a salvage value practically equal to that of copper.

Alloys of aluminum may also be used for conductors. Small percentages of silicon, magnesium, iron, copper, etc, added to aluminum, materially increase its hardness and tensile strength. The conductivity is thereby reduced, however, as it is with copper. Its elastic properties are the same as aluminum, which is not generally in its favor as a high strength conductor, as will be pointed out below. Aluminum alloys have not been employed to any considerable amount in this country but have had some use abroad.

Characteristics of Conductor Materials.—Table XX contains some of the most important characteristics of the various conductor materials which have been described above. Following that, a brief discussion of each of these characteristics in its relation to the mechanical design of overhead lines will be given.

Conductivity.—Since the major function of any conductor is to transmit electrical current, in comparing any two conductor materials, sizes of equivalent conductivity should be chosen, rather than sizes of equal cross-sectional area. Usually copper is used as the standard as it has the highest conductivity of any of the commercial conductor materials and is the material most commonly employed. For example, taking No. 2 copper as a basis, the equivalent sizes of other materials are as follows to the nearest standard size:

No. 2 Copper Equivalent (R = 0.161 ohms per 1,000 ft.)

Copper	No. 2 (A.W G)
Aluminum	No 0 (A W.G.)
Copper-covered steel·	
30 per cent	No. 0000 (A W.G.)
40 per cent	No. 000 (A.W G.)
Copper-alloy (Hitenso)	No. 1 (A.W.G)
Aluminum alloy (Aldrey)	No. 00 (A.W G.)

Weight.—The weight of the wire is one of the important factors in the study of sags and tensions in conductors. For a given deflection in a span, the tension in the wire is practically in direct proportion to the load per foot on the wire, and this load consists of the weight of the wire itself plus its insulation or covering, plus ice loading, plus (vectorially) wind loading. The ratio between tensile strength and weight is a rough indication of the mechanical advantage of any conductor material.

Ultimate Strength.—The ultimate strength of a conductor, while a measure of its resistance to breakage under unusual loading, is not especially important in studying a design since ultimate strength is not reached without appreciable elongation of the wire. Elongation, even in very small percentage, is accompanied by comparatively large increase in sag. Since tension is approximately inversely proportional to sag, when the sag increases the tension, and hence the stress in the wire, decreases. The elongation up to the elastic limit is taken into account in computing allowable sags, etc. Beyond that point, the elongation, being much greater per unit increase in stress and being partly permanent, cannot, as a rule, be included as a factor in design. The ultimate strength of stranded conductor is usually assumed to be about 90 per cent of the sum of the strength of the strands.

Elastic Limit.—The elastic limit of a conductor is the maximum stress which it ordinarily should be required to withstand. Theoretically, a conductor may be stressed up to its elastic limit without permanent deformation, *i e*, when the stress is removed it should return to its original unstressed length.

True elastic limit is, therefore, the stress at which the stress-strain curve starts to diverge from the straight line which is its form at low values of stress. For conductor materials such as copper or aluminum this point is at a fairly low stress, the shape of the curves being approximately as shown on Figs. 224 and 225. Beyond that point, the increase in curvature is more or less gradual for some distance, that is, although the material is permanently elongated by increase in stress, a considerable increase must be imposed before the "yield point" is reached where it will draw out and break without further increase. As a rule, the elastic limit is taken at some point where "the tangent to the curve has a slope 1.5 times that of the curve up to the true elastic limit."[1] It is commonly assured that, if the wire is stressed somewhat beyond the true elastic limit, to a point *a*, Fig. 224, for example, when the stress is released the stress-strain curve will return along a straight line parallel to the initial curve and subsequent stressing up to that point will follow that line, at least nearly up to the original curve. Somewhat of an increase in the true elastic limit is therefore obtained by initially stressing the wire to somewhere near its assumed elastic limit and this is

[1] Johnson's elastic limit.

sometimes practiced. The elastic limit of copper is generally assumed as from 50 to 60 per cent of its ultimate breaking strength for medium- and hard-drawn copper (Safety Code gives 55 per cent). For soft-drawn the elastic curve has an even smaller straight portion and hence the elastic limit is very indefinite but is, for practical purposes, usually assumed at about 50 per cent of the ultimate. For aluminum the elastic limit is also indefinite but is taken as from 50 to 65 per cent of the ultimate stress.

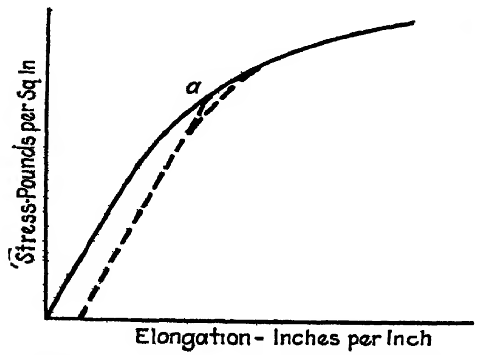


FIG. 224.—Stress strain curve—hard drawn copper

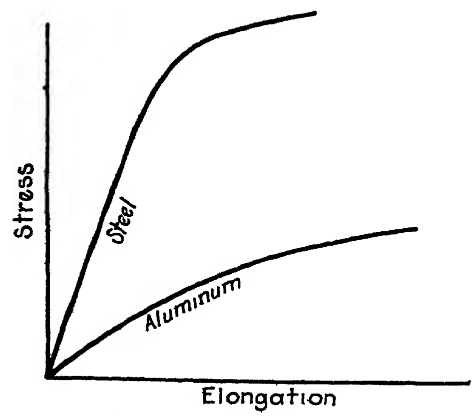


FIG 225.—Stress strain curve—steel and aluminum.

For composite materials such as A.C.S.R., the stress-strain curve is a combination of the curves of the two materials, Fig. 225. On initial stress, the two components will elongate equally, hence will divide the stress in proportion to their cross-sectional area and their individual stress-strain characteristics. For example, assume there is 1 strand of steel and 6 of aluminum, and the aluminum elongates $^{29}\!/_9$ times as much for the same stress as does the steel (ratio of moduli of elasticity, E).

The load assumed by 1 steel strand

$$= \frac{29}{9} \times \frac{\text{the load assumed by 6 aluminum strands}}{6}$$

$$= {}^{29}\!/_{54} \times \text{the load assumed by 6 aluminum strands;}$$

i.e., the steel takes $^{29}\!/_{83}$ of the total load, the aluminum $^{54}\!/_{83}$.

When a certain stress is reached, the aluminum portion will pass its elastic limit and will thereafter elongate more rapidly in

proportion to the increase in stress. The steel having a higher elastic limit will therefore assume a continually increasing proportion of the load until its elastic limit is reached. Figure 226 shows typical stress-strain curves for such a wire. If the stress is released at the point *a*, the aluminum will return to zero stress along a line *b*, having a permanent elongation. The steel will return to zero stress along the line *c*, the aluminum strands loosening somewhat to compensate for their increased length. The composite wire will follow the curve *d*. For subsequent loading, the material will follow approximately the composite curve by

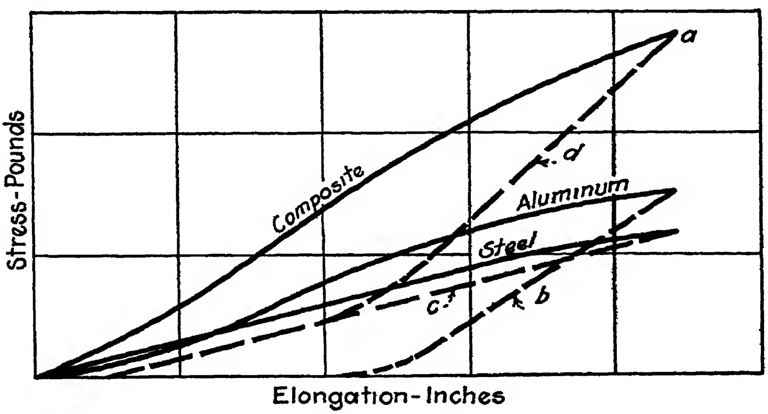


FIG. 226.—Stress strain curve—A.C S.R

which it returned from the initial stress unless such subsequent stress loads it beyond the point *a*. The elastic limit of the composite material is a rather indefinite quantity as is readily seen from these curves. It might be assumed to be at the elastic limit of the steel component since, up to that point, the behavior of the material will be very much as illustrated in Fig. 226. The manufacturers, figures for elastic limit are about 70 per cent of those for ultimate strength.

Modulus of Elasticity (*E*).—The ratio between stress in pounds per square inch and elongation per unit length is the measure of the elasticity of the material. It is the slope of the straight-line section of the stress-strain curve up to the elastic limit. For A.C.S.R. it is practically impossible to state the modulus of elasticity, except approximately, since the stress, strain curve is composite as has been shown.

The modulus of elasticity is a measure of the way a conductor will sag under loading. A low modulus indicates that a relatively large sag may be expected when the wire is loaded, a high modulus indicates comparatively small increase in sag between lightly loaded and heavily loaded conditions (temperature neglected). Aluminum has a much lower modulus than copper, hence it is to be expected that it will show a greater increase in sag when loaded with ice and wind. This is a factor which should be taken carefully into account when designing a line. Designs are usually based on ground clearances, etc., at 60°F. but in many locations the clearances under ice loading are equally important. The high-tensile-strength aluminum alloys have this disadvantage that their modulus of elasticity is practically the same as that of pure aluminum. Hence they show a relatively large increase in sag under load.

Temperature Coefficient of Linear Expansion.—This characteristic is a measure of the change in length of the material with temperature. It is of prime importance in studying the variations in sags of a conductor with temperatures other than that in which it is strung. A high coefficient means relatively large increase. It is sometimes found that the sag at high summer temperatures is greater than that under heavy ice loading, for which the temperature is of course low, and this may be a critical feature of the design. Here again aluminum, and its alloys are at somewhat of a disadvantage as this coefficient of expansion is considerably greater than that of copper

Covering and Insulation.—A clear distinction should be made between insulated wire and wire which can be called only "covered" wire. Insulated wire has a covering of definite insulating value intended to be sufficient to withstand under all ordinary conditions of service, with a reasonable safety factor, the voltage imposed. Covered wire as used on distribution lines is usually the so-called "weatherproof" wire. Such covering may have some insulating value under favorable conditions but cannot be said to be an insulation, since its dielectric strength is usually very uncertain and variable.

Weatherproof Covering.—*Weatherproof* or, as it would be more accurately designated, *weather-resisting* covering consists of cotton braids woven about the wire and impregnated with a waterproof compound. Jute is sometimes used for inner braids. The various thicknesses of covering used are designated by the

number of braids as "single braid," "double braid," and "triple braid" No generally accepted standards exist at present for either the thickness and quality of the braids or the composition and properties of the impregnating compound. There are two rather distinct groups among the users of weatherproof wire There are those who believe the covering is useful only when new and who do not think it worth while to pay extra for the qualities which might insure long life and retention of such insulating value as it has. Others feel that the weatherproofing, if used at all, should be of sufficiently good quality to have a reasonably long serviceable life. For secondary voltages, *i.e.*, up to 500 volts, good weatherproofing may be considered to be quite effective insulation and as such should, it would seem, retain its effectiveness as long as the wire is used. For voltages around 2,300 volts, weatherproofing on the wires, while not a dependable insulation, will be sufficient to avoid many troubles due to wires swinging together, coming in contact with trees, etc. For higher voltages, especially of the order of 5,000 or above, weatherproofing cannot be considered as insulation and many companies use bare wire. For voltages around 5,000, good triple-braid weatherproofing may be quite effective when *new* and *dry* and hence is of some value in urban districts, and especially on poles with many wires, in preventing accidental faults when stringing in new circuits or from objects thrown across the wires. As a protection to workmen or the public, however, it cannot be depended upon. For rural lines bare wire is quite generally employed. Where weatherproofing on wire is used for its insulating properties, triple braid is probably preferable to single- or double-braid, since the insulating value will be more or less in proportion to the thickness of the covering.

A few points might be noted in connection with the qualities desirable in weatherproofing. In purchasing wire, a limit should be placed on the weight of the weatherproofing for any given size of wire, since, as a matter of economy, a user should not purchase a greater proportion of such material than is necessary for his purpose. The compound used should be fairly elastic at all temperatures, solid enough not to drip at high temperature, should be insoluble in water, and should not contain anything which would tend to injure or deteriorate the cotton.

Insulation.—Insulated wire used on distribution circuits is mostly for training wires on transformer poles, cable poles, etc.,

for jumpers, and in general where it is subject to considerable handling or in locations where men are likely to come in frequent contact with it. Interior wiring is of course the greatest use for insulated wire.

Insulation for outdoor use usually consists of a layer of rubber surrounding the wire, covered by one or two weatherproof braids. The thickness of rubber required for various voltages as given in the A.I.E.E. Standards is as follows:

	600 volts	1,500 volts	2,500 volts	3,500 volts	5,000 volts	6,000 volts
Nos. 14 to 8	3/64	6/64	8/64	10/64	12/64	14/64
Nos. 7 to 2	4/64	7/64	9/64	10/64	12/64	14/64
Nos. 1 to 0000	5/64	8/64	10/64	10/64	12/64	14/64
225 to 500 M. cir. mils.	6/64	9/64	10/64	11/64	12/64	14/64
550 to 1,000 M. cir. mils	7/64	10/64	10/64	12/64	12/64	14/64
1,250 to 2,000 M. cir. mils	8/64	10/64	10/64	12/64	14/64	16/64

	7,000 volts	8,000 volts	9,000 volts	10,000 volts	11,000 volts
Nos. 14 to 8.	16/64	18/64	20/64	22/64	24/64
Nos. 7 to 2	16/64	18/64	20/64	22/64	24/64
Nos. 1 to 0000	16/64	18/64	20/64	22/64	24/64
225 to 500 M. cir. mils	16/64	18/64	20/64	22/44	24/64
550 to 1,000 M. cir. mils	16/64	18/64	20/64	22/64	24/64
1,250 to 2,000 M. cir. mils	18/64	18/64	20/64	22/64	24/64

While these thicknesses are generally accepted for use on interior wiring, they are sometimes reduced when applied to special purposes on distribution lines, some allowance being made for the insulating value of the pole, and for high quality rubber, if used. Rubber insulation is subject to deterioration when exposed to changes in temperature, moisture, and sunlight and for outdoor use it is usually advisable to use a higher grade than the ordinary so-called "National Electrical Code Rubber," such as that which is specified as 30 per cent Hevea or its equivalent.

Tree Wire.—Where wires pass through trees and are subject to abrasion from limbs and branches as well as to being grounded through the tree, some form of covering is necessary to resist these actions. Several forms of tree wire are on the market. The covering usually consists of a layer of rubber of sufficient thickness to insulate for the voltage used, covered by some abrasion resisting material. Several forms of coverings are being produced such as hard-woven cotton braids, fiber armor, sisal, and other specially prepared materials. Sometimes a wooden molding is used around the wire as an abrasion resistant at points where damage is especially likely, the wire used being either some form of tree wire or, in some cases, ordinary insulated wire. It should be remembered in using tree wire that the loading on the wire is considerably larger than for ordinary weatherproof wire and sags and tensions must be computed accordingly.

Conductor Size.—In this country, the *circular mil* is usually used as the unit of measurement in defining conductor sizes. For the smaller conductors, up to 212,000 cir. mils, the size is usually designated by a gauge number according to the standard American Wire Gauge (A.W.G.). For the large sizes, the cross-sectional area in circular mils is used to describe the size of the conductor. One thousand circular mils is quite often used as a unit and a size written as 350M. c.m. for example, referring to 350 thousand circular mils or 350,000 C. M. Since tensile strength of a wire is a function of cross-sectional area and unit strength is usually given in pounds per square inch, it is often necessary to convert circular mils to square inches, to determine diameters in inches, etc. In foreign practice the metric scale is used for diameters and areas and a ready means of comparing sizes so given with those denoted in inches or circular mils is often useful. The following definitions and relations will be found convenient.

A linear mil $= 0.001$ in.
$\doteq 0.0254$ millimeter.

A circular mil = the area of a circle 1 linear mil in diameter

$$= \frac{\pi}{4} \text{ square mils.}$$

$$= \frac{\pi}{4} \times 0.000001 \text{ square inch} = 0.7854 \times 10^{-6} \text{ square inch.}$$

Cross-sectional area in square inches $= \frac{\pi}{4}$ (diameter in inches),^{2} for solid wire

$= \frac{\pi}{4}\,\frac{(\text{diameter in linear mils})^2}{1{,}000}$, for solid wire

$= 0.7854 \times 10^{-6} \times$ cross-sectional area in *circular mils*.

$= 645.1 \times$ cross-sectional area in square millimeters.

Diameter (of solid wire) in inches $=$ diameter in linear mils $\times$ 1,000

$= \sqrt{\frac{\text{cross-sectional area in circular mils}}{1{,}000}}$

$= \sqrt{\frac{\text{cross-sectional area in square inches}}{0.7854}}$.

$= 0.03937 \times$ diameter in millimeters.

Cross-sectional area in square millimeters $= \frac{\pi}{4}$ (diameter in millimeters)^2

$= 645.1 \times$ cross-sectional area in square inches.

$= \frac{\text{cross-sectional area in circular mils}}{1{,}973}$

Diameter in millimeters $= 25.3997 \times$ diameter in inches

$= 0.0254 \times \sqrt{\text{cross-sectional area in circular mils}}$

$= \sqrt{\frac{\text{cross-sectional area in square mils}}{0.7854}}$

Diameter of stranded wire = approximately, 15 per cent greater than diameter of solid wire of the same cross-sectional area.

American Wire Gauge.—Formerly known as the Browne and Sharpe Gauge (B. & S.) but now more generally called the American Wire Gauge (A.W.G.), this gauge or tabulation of sizes is the standard for American manufacturers and users. It is based on the formula,

$$\text{Diameter in inches} = \frac{0.3249}{1.123^n}.$$

$$\text{Cross-sectional area in circular mils} = \frac{105{,}500}{1.261^n},$$

where

n = gauge number (No. 00 = −1, No. 000 = −2, No. 0000 = −3).

The A.W.G. sizes larger than No. 12 are given in Table XXI. It may be noted that the diameter doubles approximately for each sixth size (No. 1 has twice the diameter of No. 7) and the cross-sectional area therefore doubles for each third size, and is multiplied by four for each sixth size (No. 1 has twice the area of No. 4 and four times that of No. 7).

TABLE XXI.—DIAMETER AND CROSS-SECTIONAL AREA OF A W G. SIZES OF SOLID WIRE

A.W G number	Cross-sectional area			Diameter	
	Circular mils	Square inches	Square millimeters	Inches	Millimeters
0000	211,600	0 166190	107 219	0 4600	11 683
000	167,772	0 131770	85 011	0 4096	10 404
00	133,079	0 104520	67 432	0 3648	9 266
0	105,625	0 082958	53 521	0 3250	8 255
1	83,694	0.065733	42 408	0 2893	7 348
2	66,358	0 052117	33 624	0 2576	6 543
3	52,624	0 041331	26 665	0 2294	5.827
4	41,738	0 032781	21 149	0 2043	5 189
5	33,088	0 025987	16 766	0 1819	4.620
6	26,244	0 020612	13 298	0 1620	4.115
7	20,822	0 016354	10 550	0 1443	3.665
8	16,512	0 012969	8 3666	0 1285	3.264
9	13,087	0 010279	6 6313	0 1144	2.906
10	10,384	0 0081553	5 2614	0 1019	2.588
11	8,266.5	0 0064611	4 1684	0 0907	2.304
12	6,528.6	0 0051276	3 3081	0 0808	2 052

Solid wire is usually not made in sizes larger than No. 0000 and for distribution lines it is usually convenient to use stranded wire for sizes larger than No. 2 or thereabouts.

Table XXII gives similar data for stranded wire including the larger sizes. For some of the sizes, two different strandings are both quite commonly used and are both given in the table.

TABLE XXII —DIAMETER AND CROSS-SECTIONAL AREA OF STRANDED WIRE

A.W.G. number	Cross-sectional area			Number of strands and diameter	Diameter	
	Circular mils	Square inches	Square millimeters		Inches	Millimeters
	1,000,000	0 785398	506 660	61 × 0 128	1 15	29 210
	750,000	0 589049	379 996	61 × 0 111	0 998	25 350
	500,000	0 392699	253 330	37 × 0 116	0 813	20 650
	450,000	0 353429	278 663	37 × 0 110	0.772	19 601
	400,000	0 314159	202 664	37 × 0 104	0 728	18 491
	350,000	0 274889	227 997	37 × 0 097	0.681	17 297
				19 × 0 136	0.678	17 221
	300,000	0 235619	151 998	37 × 0 090	0 630	16 002
				19 × 0.126	0 628	15 951
	250,000	0 196350	126 665	37 × 0.082	0 575	14 605
				19 × 0.115	0 573	14 554
No. 0000	211,600	0 166190	107 219	19 × 0.106	0 528	13 411
				7 × 0.174	0 522	13 259
No. 000	167,772	0 131770	85 011	19 × 0.094	0 470	11 938
				7 × 0.155	0 464	11 786
No 00	133,079	0 104520	67 432	19 × 0 084	0 418	10 617
				7 × 0 138	0.414	10 516
No. 0	105,625	0 082958	53 521	19 × 0 075	0 373	9 474
				7 × 0 123	0 368	9 347
No. 1	83,694	0 065733	42.408	19 × 0 066	0 332	8 433
				7 × 0 109	0 328	8 331
No. 2	66,358	0 052117	33.624	7 × 0 097	0 292	7 417
No. 3	52,624	0 041331	26 665	7 × 0 087	0 260	6 604
No. 4	41,738	0 032781	21.149	7 × 0 077	0 232	5 893
No 5	33,088	0 025987	16.766	7 × 0 069	0 207	5 258
No. 6	26,244	0 020612	13 298	7 × 0 061	0 184	4 574

Minimum and Maximum Sizes.—The size of conductor to be used on a distribution circuit is usually governed quite largely by the electrical load to be transmitted and the allowable voltage drop. The requirements for mechanical strength, however, place a minimum on the size which it is practicable to use. The minimum, of course, depends on the kind of material of which the conductor is composed and the loading to which it is to be subjected. The Safety Code specified the minimum sizes shown in Table XXIII where sags as given elsewhere in the Code are used. Provision is made, however, for the use of longer spans than those given for any size of conductor if proper sags and clearances are allowed.

The grades of construction referred to are explained in Chap. XVI. The type of loading is defined on page 383:

TABLE XXIII.—MINIMUM ALLOWABLE CONDUCTOR SIZES[1]

Kind of wire	Loading district	Grade of construction	Wires sizes for span lengths up to and including: 150 ft.	175 ft.	200 ft.	250 ft	300 ft
Covered wires:							
Copper, hard drawn	Heavy	A and B	6	4	4		2
		C	8	6	4		2
Copper, medium hard	Medium	A	6	4	4		2
		B	8	6	4		2
		C	8	6	4		2
Copper-covered steel	Light	A	6	6	4		2
		B	8	6	6		2
		C	8	8	6		2
Bare wires:	Heavy	A and B	6	4	4		4
Copper, hard and medium hard		C	8	6	4		4
	Medium	A	6	6	4		4
		B	8	6	4		4
		C	8	6	4		4
Copper-covered steel	Light	A	6	6	6		4
		B	8	6	6		4
		C	8	8	6		4
Covered or bare wires:	Heavy	A	4	2	1		
		B	4	2	2		
		C	6	2	2		
Copper, soft	Medium	A and B	4	4	2	1	
		C	6	4	2	1	
	Light	A, B, and C	6	4	4	2	1
Stranded aluminum, without steel reinforcement.	All	A, B, C and N	1	0 for spans over 150 ft.			
with steel reinforcement ..	All	A, B, C, and N	6	4 for spans over 150 ft.			
				Urban		Rural	
Copper, soft ...		N		[2]6		[2]8	
Copper, hard		N		[2]8		[2]8	
Copper, medium hard..		N		[2]8		[2]8	

[1] National Electrical Safety Code

[2] These sizes are not recommended for spans over 150 ft in length

For service wires carrying 750 volts or less the minimum is given as No. 10 for soft-drawn copper, and No 12 for medium-hard- or hard-drawn, except where crossing over supply conductors of over 750 volts or over trolly contact conductors, where larger sizes are specified.

These sizes should be considered as minimums. It is often advisable to use larger sizes, even though they are not required for conductivity. A little extra mechanical strength is likely to be worth while as insurance against troubles due to broken wires. In general, it is believed that in heavy-loading districts No 6 should be the minimum for hard or medium-hard copper and No. 4 (its equivalent in conductivity) for steel-reinforced aluminum. Smaller wires are likely to be damaged in handling to such an extent as to materially impair their strength. Soft-drawn copper cannot be recommended for line wires, except perhaps in the larger sizes, since its mechanical strength is much smaller than hard-drawn or medium-hard-drawn copper and there is little compensating advantage in its use. For service wires where spans are short, sags relatively large, and joints many, soft-drawn copper is a good material.

A maximum limit of conductor size is also imposed by convenience in handling, erecting, guying, etc. As a rule No. 0000 is about as large as can be easily handled in quantity and even for that size there is considerable difficulty in getting the best construction in congested city areas where corners are numerous and where possible locations for poles and guys are limited. Larger sizes are sometimes used, especially in short lengths such as short secondaries or for service wires. The largest which can be effectively handled even in this way is about 1,000,000 cir. mils. It is sometimes more convenient for these large sizes to use two wires of smaller size rather than one large one.

Loading.—The maximum loading to which overhead conductors are subject ordinarily is due to accumulation of ice, frost, or snow on them and to wind pressure on them, either with or without such accumulation. Just what values each of these two components of load are likely to reach and in what proportion they are likely to be combined at any one time, are extremely difficult matters to determine. Certain districts seem to be much more subject to sleet storms than others even in the same general locality. In large cities sleet formation is much less likely to occur, especially in dangerous amounts, than in rural

districts. Also, the exposure of lines to wind is extremely varied, since trees, hills, buildings, etc. make more or less effective shields against the imposure of the full pressure which a wind might create in open country. Very heavy ice formation without much wind has been experienced in many cases and also very strong winds are quite likely to occur in warm weather, with no ice formation possible. The probability of the simultaneous occurrence of both types of loading in any particular degree of severity is a question which has not as yet been fully studied. The Safety Code defines three conditions of loading, *heavy*, *medium*, and

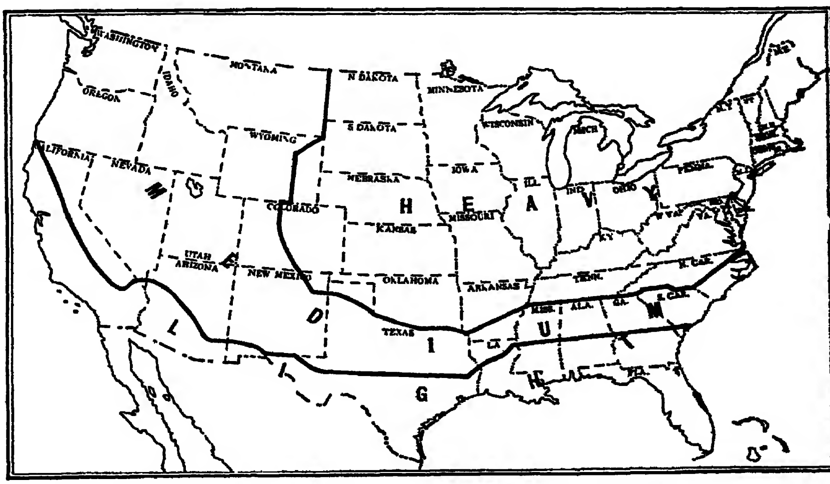


FIG 227.—Loading districts (*National Electrical Safety Code*).

light and divides the country into three areas in which these loadings are intended to be applied as shown on Fig. 227. These loadings are defined as:

Heavy loading . . .	½ in. radial thickness of ice, 8 lb. per square foot of wind on the ice-covered wires (projected area), 0°F.
Medium loading......	¼ in radial thickness of ice, 8 lb. per square foot of wind on the ice-covered wires (projected area), +15°F.
Light loading. .	No ice, 12 lb. per square foot of wind on the wires (projected area), +30°F.

It is probable that this classification is as good a one as can be made at this time for general purposes and until some more definite data than is now available can be collected. Such data is being gathered by the Overhead Systems Committee of

the National Electric Light Association and when assembled may lead to some revision in present ideas of probable loading. It must be recognized in any event that there may be many exceptions to any general rules such as the occurrence of heavy-loading districts in light-loading territory, etc.

Ice loading may occur in several different forms. The most common is sleet, which is the formation of solid ice on the wire by the freezing of moisture which is falling as rain. Another type is frost which in its troublesome form is of much less common

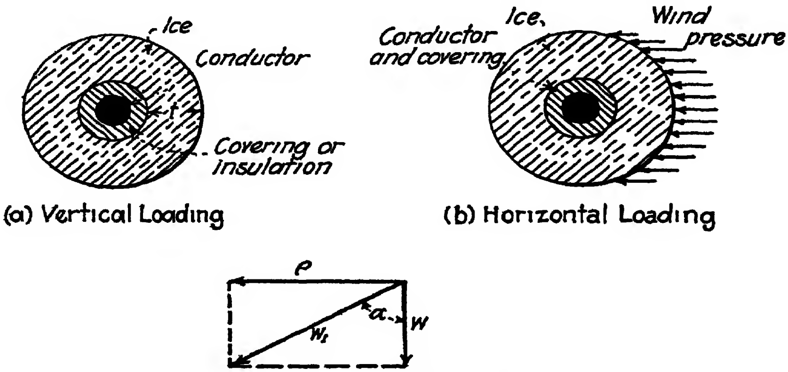


FIG. 228 —Loading on wires.

occurrence than sleet. It collects on the wire in a loosely packed mass of less weight per unit thickness than sleet but of much larger diameter. A third type is wet snow which, under certain conditions, may cling to wires, building up to a comparatively large diameter. Since sleet is the most common form and the one whose characteristics are best known, it is generally used as the basis for computation. The weight of sleet formation is assumed to be the same as ice, *i.e.*, 57 lb. per cubic foot.

The *vertical load* on a conductor consists, therefore, of:

w = weight of conductor.
+ weight of covering or insulator
+ weight of ice,
see Fig. 226 (*a*).

$$\text{Weight of ice} = \frac{\pi}{4}[(d + 2t)^2 - d^2]\frac{57}{144} = 1.243(dt + t^2) \text{ lb. per foot length} \quad (80)$$

where

d = diameter of wire and covering in inches.
t = thickness of ice in inches, assuming symmetrical formation.

The *horizontal load* on the conductor consists of the wind pressure per square foot multiplied by the projected area of the conductor with its covering of ice, if any, see Fig. 228 (*b*).

$$\text{Wind pressure} = p = \frac{(d + 2t)}{12} \times f \text{ lb. per foot length} \tag{81}$$

where

f = the assumed unit wind pressure per square foot.

Wind pressure depends on its velocity and may be computed by the formula

$$f = 0.0025v^2 \tag{82}$$

where

v = actual velocity in miles per hour.

It is evident that an 8-lb per-square-foot pressure corresponds approximately with a velocity of 60 miles per hour and a 12-lb. pressure with 70 miles per hour.

If

$$f = 8 \text{ lb. per square foot,}$$
$$\text{wind pressure} = p = \tfrac{2}{3}(d + 2t).$$

The *resultant load* on the wire is the vector sum of the vertical and horizontal components and acts at an angle to the vertical, whose size depends on the relative sizes of the two components, see Fig. 228 (*c*).

$$W = \sqrt{p^2 + w^2} \tag{83}$$

$$\alpha = \tan^{-1}\frac{p}{w}. \tag{84}$$

Example.—No. 0 stranded, triple-braid weatherproof wire.
Heavy-loading district.
Weight of bare conductor = 0.326 lb. per foot
Weight of weatherproof covering = 0 098 lb. per foot.
Weight of wire and covering = 0 424 lb. per foot
Diameter of wire and covering = 0.605 in.
Weight of ½ in. radial thickness of ice = 1.243 (0 605 × ½ + ½²) = 0.687 lb. per foot.
Total weight of wire and ice = w = 1.111 lb. per foot.
Horizontal wind pressure at 8 lb. per square foot
= ⅔(0.605 + 1.0) = 1.070 lb. per foot.
Resultant loading = $\sqrt{1.070^2 + 1.111^2}$ = 1.542 lb. per foot.
Angle of resultant to vertical = $\alpha = \tan^{-1}\dfrac{1.070}{1.111}$
= $\tan^{-1}$ 0 963 = 43 deg. 55 min., approximately.

Tables XXIV to XXXIII inclusive give wire loadings for various kinds of wire and the three degrees of loading of the Safety Code.

Short Spans.—Where spans are comparatively short, and especially with high strength conductors, the sags computed on the basis of reaching the elastic limit of the material under maximum loading may be so small that the wire is likely to be easily overstressed by small movements of the pole top under wind, etc. For such cases an increase in sag from that theoretically determined is practically advisable to prevent such overstressing.

Vibration Loading.—There is another form of loading to which wires in spans are subjected and about which there is, to date, little data available. Under certain conditions, wind will cause the wires to vibrate up and down in a vertical plane (or nearly so). This vibration is of a harmonic nature, seeming to be related in some way to the natural period of vibration of the span. The whole span may vibrate as a unit or it may be divided into two or more sections, each vibrating, with points of no motion between. The vibrations sometimes reach considerable amplitude, of the order of 2 or 3 ft. or more, and it is evident that the stresses thus imposed on the conductors may be considerable. This phenomenon has as yet not been studied sufficiently to enable any definite laws to be established regarding its occurrence. (Cases of its occurrence are relatively rare.) It usually happens when there is some ice load on the wire, but not necessarily with very heavy ice or very heavy wind. It is mentioned here as a matter of interest, but nothing further can be said at this time as to how it may be foreseen or prevented.

Strength of Conductors.—The ultimate strengths of various conductors are given in Tables XXIV to XXXIII, inclusive. The Safety Code stipulates that conductors shall be given such sags that, under the assumed worst loading, the stress will not exceed 50 per cent of the breaking strength for Grades A and B construction and 60 per cent for Grade C. These percentages of the breaking strength give approximately the elastic limit where copper wire is used. The rule is based on the fact that if the assumed maximum load is such that the elastic limit will be exceeded, the conductor, if subjected to such loading, will be given a permanent elongation. This not only will require the excess sag to be pulled up when normal conditions are resumed, but causes a reduction in effective cross-sectional area of the conductor. It is only a reasonable precaution, no matter what

Table XXIV.—Characteristics of Copper Wire
Solid—Bare

Size, A.W G.	External diameter, inches	Area of conductor, square inches	Hard drawn	Soft drawn	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
			Ultimate tension, pounds	Ultimate tension, pounds	Vertical, conductor only	Horizontal, wind 8 lb per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb per square foot, ½ in ice	Resultant
0000	0 460	0 1662	8,140	5,980	0 641	0 306	0 460	0 711	0 788	0 862	0 640	1 074	1 239	0 973	1.575
000	0 410	0 1318	6,720	4,740	0.508	0.273	0 410	0 576	0 653	0 713	0 607	0 936	1 075	0 940	1 427
00	0 365	0 1045	5,520	3,760	0 403	0 243	0 365	0.471	0 544	0 594	0 577	0 828	0 942	0 910	1 309
0	0 325	0 0829	4,520	2,980	0 319	0 216	0 325	0 386	0.455	0 498	0 550	0 742	0 833	0 884	1 214
1	0 289	0 0657	3,690	2,360	0 253	0.193	0.289	0.318	0 385	0.421	0.526	0.674	0 744	0 859	1 137
2	0 258	0 0521	3,000	1,930	0 201	0 172	0.258	0 265	0 327	0 359	0 505	0 620	0 673	0 839	1 075
3	0 229	0 0413	2,440	1,530	0 159	0 153	0 229	0 221	0 280	0 308	0 486	0 575	0.613	0 819	1 023
4	0 204	0.0328	1,970	1,210	0.126	0 136	0 204	0 186	0 240	0 267	0 469	0 540	0 564	0 802	0 981
5	0 182	0 0260	1,590	960	0 100	0 121	0 182	0 157	0 208	0 234	0 455	0 512	0 525	0 788	0 946
6	0 162	0 0206	1 280	760	0.0795	0 108	0.162	0 133	0 180	0 208	0 441	0 488	0 491	0 775	0 917
7	0 144	0 0163	1,030	.....	0 0630	0 096	0.144	0.114	0.157	0.185	0.429	0 467	0 464	0 763	0 893
8	0 128	0 0130	830		0 0500	0 085	0 128	0 098	0 137	0 167	0 419	0 451	0 441	0 752	0 873

TABLE XXV.—CHARACTERISTICS OF COPPER WIRE

STRANDED—BARE

Size, A W G. or circular mils	External diameter, inches	Area of conductor, square inches	Hard drawn	Soft drawn	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
			Ultimate tension, pounds	Ultimate tension, pounds	Vertical, conductor only	Horizontal, wind 8 lb. per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb. per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb. per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb per square foot, ½ in ice	Resultant
500,000	0.814	0.3924	22,710	13,070	1.540	0.543	0.814	1.633	1.742	1.871	0.876	2.066	2.357	1.209	2.649
450,000	0.772	0.3535	20,460	11,770	1.390	0.515	0.772	1.482	1.590	1.708	0.848	1.907	2.181	1.182	2.481
400,000	0.728	0.3143	18,330	10,470	1.240	0.485	0.728	1.331	1.438	1.544	0.819	1.748	2.004	1.152	2.311
350,000	0.681	0.2741	16,040	9,530	1.080	0.454	0.681	1.172	1.277	1.369	0.787	1.579	1.815	1.121	2.133
300,000	0.630	0.2354	13,860	8,160	0.926	0.420	0.630	1.017	1.120	1.200	0.753	1.417	1.629	1.087	1.958
250,000	0.575	0.1964	11,610	6,810	0.772	0.383	0.575	0.862	0.963	1.029	0.717	1.254	1.441	1.050	1.783
0000	0.528	0.1662	9,690	5,760	0.653	0.352	0.528	0.742	0.840	0.895	0.685	1.127	1.292	1.019	1.645
000	0.470	0.1318	7,760	4,570	0.518	0.313	0.470	0.605	0.699	0.742	0.647	0.984	1.121	0.980	1.489
00	0.418	0.1045	6,180	3,620	0.411	0.279	0.418	0.496	0.586	0.619	0.612	0.871	0.982	0.945	1.363
0	0.373	0.0829	4,920	2,870	0.326	0.249	0.373	0.410	0.495	0.520	0.582	0.781	0.870	0.915	1.262
1	0.332	0.0657	3,910	2,280	0.258	0.221	0.332	0.340	0.420	0.439	0.555	0.712	0.776	0.888	1.179
2	0.292	0.0521	3,040	1,810	0.205	0.195	0.292	0.283	0.357	0.374	0.528	0.647	0.698	0.861	1.108
3	0.260	0.0431	2,440	1,430	0.163	0.173	0.260	0.238	0.307	0.322	0.507	0.601	0.636	0.840	1.054
4	0.232	0.0328	1,940	1,140	0.129	0.155	0.232	0.203	0.265	0.279	0.488	0.562	0.584	0.821	1.008
5	0.206	0.0260	1,550	900	0.102	0.137	0.206	0.171	0.230	0.244	0.471	0.530	0.541	0.804	0.969
6	0.184	0.0206	1,230	710	0.0810	0.123	0.184	0.147	0.201	0.216	0.456	0.505	0.506	0.789	0.938
7	0.164	0.0164	980	..	0.0643	0.109	0.164	0.126	0.176	0.193	0.443	0.483	0.477	0.776	0.911
8	0.146	0.0130	780		0.0510	0.097	0.146	0.110	0.155	0.174	0.431	0.465	0.453	0.764	0.88

TABLE XXVI.—CHARACTERISTICS OF COPPER WIRE
SOLID—DOUBLE BRAIDED—WEATHER-RESISTING

Size, A.W G	External diameter, inches	Area of conductor, square inches	Hard drawn	Soft drawn	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
			Ultimate tension, pounds	Ultimate tension, pounds	Vertical, conductor only	Horizontal, wind 8 lb per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb per square foot, ½ in ice	Resultant
0000	0 650	0 1662	8,140	5,980	0 723	0 433	0 650	0 842	0.972	1.003	0 767	1 263	1 437	1 100	1 810
000	0 610	0 1318	6,720	4,740	0 587	0 406	0 610	0 714	0 847	0 844	0 740	1 122	1 276	1 073	1 667
00	0 545	0 1045	5,520	3,760	0 467	0 363	0 545	0 592	0 718	0 714	0 697	0 998	1 115	1 030	1 518
0	0 500	0 0829	4,520	2,980	0 377	0 333	0 500	0 503	0 626	0 610	0 667	0 904	0 997	1 000	1 412
1	0 435	0.0657	3,690	2,360	0 294	0 290	0 435	0 413	0 525	0 507	0 623	0 803	0 874	0 957	1 296
2	0.400	0 0521	3,000	1,930	0 239	0 267	0 400	0 358	0 461	0 441	0 600	0 745	0 797	0 933	1 227
3	0 345	0 0413	2,440	1,530	0 185	0 230	0 345	0 295	0 391	0 370	0 563	0 674	0 709	0 897	1 143
4	0 325	0 0328	1,970	1,210	0 151	0 217	0 325	0 264	0 358	0 330	0 550	0 641	0 663	0 883	1 104
5	0 300	0 0260	1,590	960	0 122	0 200	0 300	0 234	0 324	0 293	0 533	0.608	0 618	0.867	1.065
6	0 280	0 0206	1.280	760	0 100	0 187	0 280	0 212	0 297	0.265	0 520	0 584	0 583	0 853	1 033
7	0 260	0.0163	1,030	.....	0 088	0 173	0 260	0 194	0 275	0 247	0 507	0 564	0 559	0 840	1 009
8	0 240	0.0130	830	.....	0 066	0 160	0.240	0 173	0 249	0 218	0 403	0 539	0 525	0 827	0 980

TABLE XXVII.—CHARACTERISTICS OF COPPER WIRE
STRANDED—DOUBLE BRAIDED—WEATHER-RESISTING

Size, A.W G	External diameter, inches	Area of conductor, square inches	Hard drawn	Soft drawn	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
			Ultimate tension, pounds	Ultimate tension, pounds	Vertical, conductor only	Horizontal, wind 8 lb. per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb per square foot, ½ in ice	Resultant
0000	0 710	0 1662	9,690	5,760	0.745	0 473	0 710	0 882	1 029	1 043	0 807	1 319	1 495	1 140	1 880
000	0 660	0.1318	7,760	4,570	0 604	0 440	0 660	0 748	0 894	0 887	0 773	1 177	1 324	1 107	1 726
00	0 600	0 1045	6,180	3,620	0 482	0 400	0 600	0 626	0 770	0 746	0 733	1 046	1 165	1 067	1 580
0	0.540	0 0829	4,920	2,870	0 388	0.360	0 540	0 528	0 665	0 634	0 693	0 939	1 033	1 027	1 457
1	0.470	0 0657	3,910	2,280	0.303	0 313	0 470	0 436	0 559	0 523	0 647	0 832	0 904	0 980	1 333
2	0 430	0 0521	3,040	1,810	0 246	0 287	0 430	0 378	0 495	0 457	0 620	0 770	0 823	0 953	1 259
3	0 360	0 0413	2,440	1,430	0 190	0 240	0.360	0 306	0 407	0 380	0 573	0 688	0 724	0 907	1 160
4	0 330	0 0328	1,940	1,140	0 155	0 220	0.330	0 269	0 365	0 335	0 553	0 647	0 670	0 887	1 112
5	0 310	0 0260	1,550	900	0 126	0 206	0 310	0 242	0 335	0 300	0 540	0 618	0 628	0 873	1 075
6	0 290	0 0206	1,230	710	0 103	0 193	0 290	0 219	0 308	0 271	0 526	0 592	0 593	0 860	1 045
7	0 271	0.0163	980	. . .	0.090	0 180	0 271	0.201	0 286	0 252	0 514	0 573	0 568	0 847	1 020
8	0 250	0 0130	780	.....	0.068	0 167	0 250	0 180	0 259	0 223	0 500	0 548	0 533	0 833	0 989

TABLE XXVIII.—CHARACTERISTICS OF COPPER WIRE
SOLID—TRIPLE BRAID—WEATHER-RESISTING

Size, A.W.G	External diameter, inches	Area of conductor, square inches	Hard drawn	Soft drawn	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
			Ultimate tension, pounds	Ultimate tension, pounds	Vertical, conductor only	Horizontal, wind 8 lb per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb per square foot, ½ in ice	Resultant
0000	0 640	0 1662	8,140	5,980	0.767	0 427	0.640	0 878	0 999	1 044	0 760	1 291	1 476	1 093	1 837
000	0 593	0 1318	6,720	4,740	0 629	0.395	0 593	0 743	0 864	0 891	0 729	1 151	1 309	1 062	1 686
00	0.515	0 1045	5,520	3,760	0.502	0.343	0.515	0.608	0 719	0.740	0 677	1 003	1 133	1 010	1 518
0	0.500	0.0829	4,520	2,980	0.407	0 333	0 500	0 526	0 645	0 640	0 667	0 924	1 029	1 000	1 434
1	0.453	0 0657	3,690	2,360	0 316	0 302	0 453	0 437	0 552	0 535	0.635	0 830	0 909	0 968	1 328
2	0.437	0 0521	3,000	1,930	0 260	0 291	0 437	0 390	0 509	0 474	0 625	0 784	0 843	0 958	1 276
3	0 406	0 0413	2,440	1,530	0 199	0 271	0 406	0 336	0.452	0 403	0 604	0 726	0 763	0 937	1 208
4	0 359	0 0328	1,970	1,210	0.164	0.239	0 359	0.290	0.395	0.353	0 573	0 673	0 698	0 906	1 143
5	0.344	0 0260	1,590	960	0.135	0 229	0 344	0 266	0 370	0 320	0 563	0 648	0 660	0 896	1.113
6	0 328	0 0206	1,280	760	0 112	0 219	0 328	0 246	0 347	0 292	0 552	0 625	0.627	0 885	1 084
7	0 293	0 0164	1,030	..	0 092	0 195	0 293	0 216	0 307	0 261	0.529	0 590	0 585	0 862	1 042
8	0 260	0 0130	830	....	0 075	0 173	0 260	0 189	0 271	0 234	0 507	0 558	0 548	0 840	1 003

Table XXIX.—Characteristics of Copper Wire
Stranded—Triple Braid—Weather-resisting

Size, A W G or circular mils	External diameter, inches	Area of conductor, square inches	Hard drawn: Ultimate tension, pounds	Soft drawn: Ultimate tension, pounds	Loading per linear foot of conductor, pounds — Light-loading district: Vertical, conductor only	Light-loading district: Horizontal, wind 8 lb per square foot	Light-loading district: Horizontal, wind 12 lb per square foot	Light-loading district: Resultant, wind 8 lb per square foot	Light-loading district: Resultant, wind 12 lb per square foot	Medium-loading district: Vertical, conductor + ¼ in. ice	Medium-loading district: Horizontal, wind 8 lb per square foot, ¼ in ice	Medium-loading district: Resultant	Heavy-loading district: Vertical, conductor + ½ in. ice	Heavy-loading district: Horizontal, wind 8 lb per square foot, ½ in ice	Heavy-loading district: Resultant
500,000	1.108	0.3924	22,710	13,070	1.894	0.739	1.108	2.033	2.194	2.316	1.072	2.552	2.894	1.405	3.217
450,000	1.070	0.3535	20,460	11,770	1.724	0.713	1.070	1.866	2.029	2.134	1.047	2.377	2.701	1.380	3.032
400,000	1.020	0.3143	18,330	10,470	1.553	0.680	1.020	1.695	1.860	1.948	1.013	2.196	2.498	1.347	2.838
350,000	0.978	0.2751	16,040	9,530	1.345	0.652	0.978	1.495	1.663	1.727	0.985	1.988	2.264	1.319	2.619
300,000	0.930	0.2354	13,860	8,160	1.174	0.620	0.930	1.328	1.498	1.541	0.953	1.812	2.064	1.287	2.432
250,000	0.862	0.1964	11,610	6,810	0.985	0.575	0.862	1.140	1.309	1.331	0.908	1.611	1.832	1.241	2.217
0000	0.785	0.1662	9,690	5,760	0.800	0.523	0.785	0.956	1.121	1.122	0.857	1.412	1.599	1.190	1.993
000	0.728	0.1318	7,760	4,570	0.653	0.485	0.728	0.813	0.978	0.957	0.819	1.260	1.417	1.152	1.826
00	0.662	0.1045	6,180	3,620	0.522	0.441	0.662	0.683	0.843	0.806	0.775	1.118	1.245	1.108	1.666
0	0.605	0.0829	4,920	2,870	0.424	0.403	0.605	0.585	0.739	0.690	0.737	1.010	1.111	1.070	1.542
1	0.518	0.0657	3,910	2,280	0.328	0.345	0.518	0.476	0.613	0.567	0.679	0.885	0.961	1.012	1.395
2	0.440	0.0521	3,040	1,810	0.270	0.293	0.440	0.398	0.516	0.484	0.627	0.792	0.855	0.960	1.285
3	0.408	0.0413	2,440	1,430	0.206	0.272	0.408	0.341	0.457	0.411	0.605	0.731	0.771	0.939	1.214
4	0.379	0.0328	1,940	1,140	0.170	0.253	0.379	0.305	0.415	0.366	0.586	0.691	0.717	0.919	1.165
5	0.351	0.0260	1,550	900	0.140	0.234	0.351	0.273	0.378	0.327	0.567	0.655	0.669	0.902	1.122
6	0.327	0.0206	1,230	710	0.115	0.218	0.327	0.246	0.347	0.294	0.551	0.625	0.629	0.885	1.086
7	0.313	0.0164	980	....	0.0959	0.209	0.313	0.230	0.327	0.271	0.542	0.606	0.602	0.875	1.062
8	0.278	0.0130	780	....	0.0783	0.185	0.278	0.201	0.289	0.242	0.519	0.573	0.562	0.852	0.970

TABLE XXX.—CHARACTERISTICS OF ALUMINUM WIRE
STRANDED—BARE

Actual size, circular mils o A.W.G	Copper equivalent, circular mils or A.W.G	External diameter, inches	Area of conductor, square inches	Ultimate tension, pounds	Loading per linear foot of conductor, pounds										
					Light-loading district					Medium-loading district			Heavy-loading district		
					Vertical, conductor only	Horizontal, wind 8 lb per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb. per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor, +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor, +½ in ice	Horizontal, wind 8 lb. per square foot, ½ in ice	Resultant
795,000	500,000	1 026	0 6244	15,000	0 747	0 684	1 026	1 013	1 269	1 144	1 017	1 531	1 696	1 351	2 168
750,000	472,000	0 994	0 5890	14,140	0.705	0 663	0 994	0 968	1 219	1 092	0 996	1 478	1 634	1 329	2 106
715,500	450,000	0 974	0 5620	13,500	0 672	0 649	0 974	0 934	1 183	1 052	0 983	1 439	1 588	1 316	2 062
636,000	400,000	0.918	0.4995	12,000	0.598	0 612	0 918	0 856	1 096	0 961	0 945	1.348	1 480	1 279	1 956
556,500	350,000	0 856	0 4371	10,500	0.523	0 571	0 856	0 774	1 003	0 867	0 904	1 253	1 367	1 237	1 844
500,000	314,500	0 810	0 3927	9,420	0 469	0.540	0 810	0 715	0 936	0.799	0 873	1 183	1 284	1 207	1 762
477,000	300,000	0 793	0 3746	9,000	0 448	0 529	0 793	0.693	0 911	0 772	0 862	1 157	1 252	1 195	1 731
397,500	250,000	0.724	0.3122	7,490	0 373	0.483	0 724	0 610	0 814	0 676	0 816	1 060	1 134	1 149	1 614
336,400	0000	0 657	0 2642	6,350	0 316	0 438	0 657	0 540	0 729	0.598	0.771	0 976	1.035	1 105	1 514
300,000	188,800	0 621	0 2356	5,650	0 282	0 414	0 621	0 501	0 682	0 553	0.747	0 929	0 979	1 081	1 458
266,800	000	0 586	0 2094	5,040	0 251	0 391	0 586	0 465	0 638	0 511	0 724	0 886	0 926	1 057	1 405
0000	00	0.522	0.1662	3,970	0 199	0 348	0 522	0 401	0 559	0 439	0 681	0 810	0 834	1 015	1.314
000	0	0 464	0 1318	3,180	0 158	0 309	0 464	0 347	0 490	0 380	0 643	0 747	0 757	0 976	1 235
00	1	0 414	0 1045	2,520	0 125	0 276	0 414	0 303	0 432	0 331	0 609	0 693	0 693	0 943	1.170
0	2	0 368	0 0829	1,990	0 099	0 245	0.368	0 264	0 381	0 291	0 579	0 648	0 639	0 912	1 114
1	3	0 328	0 0657	1,580	0 079	0 219	0 328	0 233	0 337	0 259	0 552	0 610	0 594	0.885	1 066

TABLE XXXI.—CHARACTERISTICS OF STRANDED ALUMINUM CABLE STEEL REINFORCED—BARE

Actual size, circular mils or A.W.G.	Copper equivalent, circular mils or A.W.G.	External diameter, inches	Area of aluminum, square inches	Area of steel, square inches	Elastic limit, pounds	Ultimate tension, pounds	Loading per linear foot of cable, pounds: Light-loading district: Vertical, conductor only	Light-loading district: Horizontal, wind 8 lb per square foot	Light-loading district: Horizontal, wind 12 lb per square foot	Light-loading district: Resultant, wind 8 lb per square ft	Light-loading district: Resultant, wind 12 lb per square foot	Medium-loading district: Vertical, conductor, +¼ in ice	Medium-loading district: Horizontal, wind 8 lb per square foot, ¼ in ice	Medium-loading district: Resultant	Heavy-loading district: Vertical, conductor, +½ in ice	Heavy-loading district: Horizontal, wind 8 lb per square foot, ½ in ice	Heavy-loading district: Resultant
605,000	380,500	0 953	0 4750	0 06166	14,675	21,270	0 780	0 635	0 953	1 006	1 232	1 154	0 969	1 507	1 683	1 302	2 128
500,000	314,500	0 904	0 3927	0.08963	17,400	24,080	0 777	0 603	0 904	0 984	1 192	1 136	0.936	1 472	1 650	1 269	2 082
336,400	0000	0 741	0 2642	0 06166	11,715	16,200	0 528	0 494	0 741	0 723	0 910	0 836	0 827	1 176	1 300	1 161	1 743
266,800	000	0 633	0 2092	0 02733	6,470	9,385	0 343	0.422	0 633	0 544	0 720	0.617	0 755	0 975	1 048	1 089	1 511
0000	00	0 564	0 1662	0.02776	5,940	8,435	0 295	0 376	0 564	0 478	0 637	0 548	0 709	0 896	0 957	1 043	1 415
000	0	0 501	0 1318	0.02190	4,690	6,660	0 233	0 334	0 501	0 407	0 552	0 466	0 667	0 814	0 855	1 001	1 316
00	1	0 447	0.1045	0 01744	3,730	5,300	0 185	0 298	0 447	0 351	0 484	0 402	0 631	0 748	0 774	0 965	1 237
0	2	0 398	0.0829	0 01383	2,960	4,200	0 147	0 265	0 398	0 303	0 424	0 348	0 599	0 693	0 705	0 932	1 169
1	3	0 355	0 0657	0 01097	2,355	3,340	0 117	0 237	0 355	0 264	0 374	0 305	0 570	0 646	0 649	0 903	1 112
2	4	0 316	0 0521	0 00869	1,860	2,660	0 092	0 211	0 316	0 230	0 329	0 268	0 544	0 606	0 599	0 877	1 062
4	6	0 250	0 0328	0 00547	1,170	1,665	0 058	0 167	0 250	0 180	0 260	0 214	0 466	0 513	0 534	0 832	0 990

TABLE XXXII.—CHARACTERISTICS OF COPPER-COVERED WIRE[1]

SOLID—BARE

Size, A W G	External diameter, inches	Area of conductor, square inches	Ultimate tension,	Loading per linear foot of conductor, pounds										
				Light-loading district					Medium-loading district			Heavy-loading district		
				Vertical, conductor only	Horizontal, wind 8 lb per square foot	Horizontal, wind 12 lb per square foot	Resultant, wind 8 lb per square foot	Resultant, wind 12 lb per square foot	Vertical, conductor +¼ in ice	Horizontal, wind 8 lb per square foot, ¼ in ice	Resultant	Vertical, conductor +½ in ice	Horizontal, wind 8 lb. per square foot, ½ in ice	Resultant
0000	0 460	0 1662	9,850	0 585	0 307	0 460	0 661	0 744	0 806	0 640	1 029	1 183	0 973	1 532
000	0 410	0 1318	8,280	0 467	0 273	0 410	0 541	0 622	0 672	0 607	0 906	1 034	0 940	1 398
00	0.365	0 1045	6,850	0 370	0 243	0 365	0 443	0 520	0 561	0 577	0 805	0 909	0 910	1 285
0	0 325	0 0829	5,700	0 293	0 217	0 325	0 365	0 438	0 472	0 550	0 725	0 807	0 883	1 195
1	0 289	0 06573	4,800	0.231	0 193	0.289	0 301	0 370	0 398	0 526	0 660	0 723	0 859	1 125
2	0 258	0 05213	4,000	0.184	0 172	0.258	0 252	0 317	0 342	0 505	0 610	0 656	0 839	1 065
3	0 229	0 04134	3,200	0 146	0 153	0 229	0 212	0 272	0 295	0 486	0 569	0 600	0 819	1 017
4	0 204	0 03278	2,650	0 116	0 136	0 204	0 179	0 235	0 257	0 469	0 535	0 554	0 803	0 974
5	0 182	0.02600	2,200	0.092	0 121	0 182	0 152	0 204	0 226	0 455	0 508	0 517	0 788	0 942
6	0 162	0 02062	1,800	0 073	0 108	0 162	0 130	0 178	0 201	0 441	0 484	0 485	0 775	0 914
7	0 144	0 01635	1,450	0 058	0 096	0 144	0 112	0 155	0 181	0 429	0 466	0 459	0 763	0 890
8	0 128	0.01297	1,200	0 046	0 085	0.128	0 097	0 136	0 163	0 419	0 450	0 437	0 752	0 870
9	0 114	0 01028	970	0 037	0 076	0 114	0 085	0 120	0 150	0 409	0 436	0 419	0 743	0 853
10	0 102	0.00815	800	0 029	0 068	0 102	0 074	0 106	0.138	0 401	0 424	0 403	0 735	0 838
11	0 091	0 00647	645	0 023	0.061	0 091	0 065	0 094	0 129	0 394	0 415	0 391	0 727	0 825
12	0 081	0 00513	520	0 018	0 054	0 081	0 057	0 083	0 121	0 387	0 406	0 379	0 721	0 815
14	0 064	0 00322	330	0 012	0 043	0 064	0 045	0 065	0 110	0 376	0 392	0 362	0 709	0 796

[1] Data as given by Copperweld Steel Company for Copperweld wire.

TABLE XXXIII.—CHARACTERISTICS OF COPPER-COVERED WIRE[1]
STRANDED—BARE

Size, A W G	Nominal diameter, inches	Actual external diameter, inches	Number of wires and size, A W G	Area of conductor, square inches	Ultimate tension, pounds	Loading per linear foot of conductor, pounds: Light-loading district: Vertical, conductor only	Light-loading district: Horizontal, wind 8 lb. per square foot	Light-loading district: Horizontal, wind 12 lb per square foot	Light-loading district: Resultant, wind 8 lb per square foot	Light-loading district: Resultant, wind 12 lb per square foot	Medium-loading district: Vertical, conductor + ¼ in ice	Medium-loading district: Horizontal, wind 8 lb. per square foot ¼ in ice	Medium-loading district: Resultant	Heavy-loading district: Vertical, conductor +½ in ice	Heavy-loading district: Horizontal, wind 12 lb per square foot, ½ in ice	Heavy-loading district: Resultant
	1¼	1 274	37 No. 5	0 963	81,400	3 505	0 849	1 274	3 601	3 730	3 979	1 183	4 151	4 609	1 516	4 855
	1⅛	1 134	37 No 6	0.763	66,600	2 780	0 756	1 134	2 881	3 002	3 210	1 089	3 390	3 796	1 423	4 054
	1	1 008	37 No. 7	0 605	53,650	2 210	0 672	1 008	2 310	2 430	2 601	1 005	2 788	3 148	1.339	3 421
	⅞	0 896	37 No. 8	0.480	44,400	1 754	0 597	0 896	1 850	1 970	2 110	0 931	2 306	2 622	1 264	2 911
	⅞	0 910	19 No 5	0.495	41,800	1 800	0 607	0 910	1.900	2 017	2 161	0 940	2 357	2 677	1 273	2 964
	13/16	0 810	19 No 6	0 392	34,200	1 430	0.540	0 810	1.529	1 643	1 760	0 873	1 965	2 247	1 209	2 552
	¾	0 772	19 No. †	0.354	31,200	1 285	0 515	0 772	1.384	1 499	1 603	0 848	1 810	2 076	1 181	2 388
	23/32	0 720	19 No 7	0.311	27,600	1.135	0 480	0 720	1 232	1 344	1 437	0 813	1 651	1.894	1 147	2 214
	11/16	0 681	19 No. †	0.275	25,100	1.000	0.454	0.681	1 098	1.210	1.289	0 787	1 510	1 734	1 121	2 065
	⅝	0 640	19 No. 8	0 246	22,800	0 900	0 427	0 640	0 996	1 104	1 177	0 760	1 401	1 609	1 093	1 945
	⅝	0 612	7 No. 4	0.229	18,550	0.836	0 408	0.612	0 930	1 036	1.104	0 741	1 330	1 528	1 075	1 868
	9/16	0 570	19 No. 9	0.195	18,430	0.724	0 380	0 570	0 818	0 921	0 979	0 713	1 211	1 383	1 047	1 735
	9/16	0 546	7 No. 5	0.182	15,400	0 663	0 364	0 546	0 756	0 859	0 910	0 697	1 146	1 304	1 031	1 662
0000		0 523	7 No. †	0.166	14,300	0 606	0 349	0 523	0 699	0 800	0 846	0 682	1 087	1 236	1 015	1 599
	½	0 486	7 No 6	0 144	12,600	0 526	0 324	0.486	0.618	0 716	0 755	0 657	1 001	1 139	0 991	1 510
000		0 465	7 No †	0.132	11,640	0 481	0 310	0 465	0 572	0 669	0 703	0 643	0 953	1 079	0 977	1 458
	7/16	0 432	7 No. 7	0.114	10,160	0 418	0.288	0 432	0 508	0 601	0 630	0 621	0 885	0 998	0 955	1 381
00		0 414	7 No. †	0 105	9,460	0 382	0 276	0.414	0 471	0 563	0.588	0 609	0 847	0 948	0 945	1 339
	⅝	0 384	7 No. 8	0.0910	8,400	0 332	0 256	0 384	0 419	0 508	0 529	0 589	0 792	0 882	0 923	1 277
0		0 368	7 No †	0 0829	7,780	0 302	0.245	0.368	0 389	0 476	0 494	0 579	0 761	0 842	0 912	1 241
	11/32	0 342	7 No 9	0 0719	6,790	0 267	0 228	0 342	0 351	0 434	0 451	0 561	0 720	0 791	0 895	1 194
	5/16	0 306	7 No 10	0 0571	5,600	0 209	0 204	0 306	0 292	0 371	0.382	0 537	0 659	0 710	0 871	1 124
	9/32	0 273	7 No 11	0.0452	4,550	0 166	0 182	0 273	0 246	0 320	0 329	0 515	0 611	0 647	0 849	1 067
	¼	0 243	7 No 12	0.0360	3,640	0 129	0 162	0 243	0 207	0 275	0 282	0 495	0 570	0 591	0 829	1 018
	3/16	0 192	7 No 14	0 0226	2,310	0 083	0 128	0 192	0 153	0 209	0 220	0 461	0 511	0 513	0 795	0 946

† Means special gauge wire (not an A W G size)
[1] Data as given by the Copperweld Steel Company for Copperweld wire

the grade of construction, to give the conductors sufficient sag so that their elastic limit will not be exceeded under such heavy loadings as will probably be encountered. Local conditions will determine what such loadings may be. The use of the 50 and 60 per cent limits applied to high-strength conductors such as steel-reinforced aluminum may be somewhat too restrictive, since the elastic limit of the particular material is given as about 70 per cent of the ultimate. The rated elastic limit should be a safe limit to use for such conductors where a lower figure is not required for legal restrictions of codes or regulations. Table XX gives approximate figures for elastic limits of some of these materials and the manufacturer's figures for elastic limit of A.C.S.R. are given in Table XXXI.

Sags.—Since in a given span the tension in a conductor is practically in inverse proportion to its sag, it is evident that the determination of proper sags and the corresponding tensions is the fundamental problem in mechanical design of lines. There may be some confusion in the use of the term "sag" which should be clarified. Strictly speaking the term sag should probably be applied only to the vertical component of the *deflection* of the conductor from a straight line connecting its two supports, and when those supports are on the same level. Where wind loading is a factor, the deflection is at an angle to the vertical and hence should be termed "*deflection*" rather than sag. Such deflection is quite often called *sag*, however, and usually little confusion is caused, since the true component sag is not often considered separately. When the two supports are not at the same level, there is some question as to what line should be used as basis for measuring deflection, *i.e.*, whether it should be a horizontal line through the lower support, a similar line through the upper support, or a line connecting the two supports (see Fig. 234). For the purpose here it will be satisfactory to consider the deflection as measured from a horizontal line through the upper support.

As well as being of major importance in the study of conductor tensions, sag also has a bearing on two other problems, *i.e.*, clearance above ground (or obstructions crossed, such as trees or buildings) and spacing between conductors. It is apparent, of course, that where clearance aboveground or obstructions is limited, sags will also be limited where the height of the support is fixed. The sag, either at high temperatures or under heavy-

loading conditions, is the important consideration in this case rather than the sag at 60°F. or other intermediate conditions. Where clearances are specified in the Safety Code, they usually apply to sags taken at 60°F. with no wind, but where the clearance is limited by physical conditions, such as when passing over a building, the extreme cases of loading as stated must be taken into account.

The importance of sag as a limiting factor in the allowable horizontal spacing between conductors is due, fundamentally, to the possibility of conductors whipping together when acted upon by wind. The minimum separations are given in the Safety Code by the following formulæ

For line conductors smaller than No. 2 A.W.G.,

$$\text{minimum separation} = 0.3 \text{ in. per kilovolt} + 7\sqrt{\frac{S}{3} - 8}. \quad (85)$$

For line conductors No. 2 A.W.G. or larger,

$$\text{minimum separation} = 0.3 \text{ in. per kilovolt} + 8\sqrt{\frac{S}{12}}. \quad (86)$$

Where S = the apparent sag of the conductor having the greater sag, and the separation is in inches.

Example.—Number 4 conductors at 6,600 volts and a sag of 36 in. should be separated at least $0.3 \times 6.6 + 7\sqrt{\frac{36}{3} - 8} = 1.98 + 14 = 16$ in.

The above formulæ are chiefly applicable to the larger sags (36 in. or more) since below that amount they give spacings which are too small to be practicable. In fact, the Safety Code specifies a minimum of 12 in. for supply conductors from 0 to 7,500 volts. The determination of practicable relations between sags, voltages, and separations is largely a matter of experience, since the above minimums are, of course, often smaller than will be found practicable for good operating conditions.

Sag Computations.—In computing sags and tensions in conductors, the wire is ordinarily assumed to be perfectly flexible and the loading to be uniformly applied over the whole length. If the load on such a wire is of uniform value *per unit length of wire*, the wire will assume the shape of a *catenary*. This is the assumption used for the more accurate computations. It is not entirely accurate, of course, since the wire is not perfectly flexible but it is as accurate as is necessary for any practicable

purpose If the load is assumed to be of uniform value *per unit length of span,* the shape assumed by the wire will be a *parabola* For distribution lines, the spans are usually comparatively short and the sags correspondingly small, hence little error is introduced if the load is assumed to be uniformly distributed over the length of the span rather than the length of the wire. The parabolic method will be found useful for some purposes as the formulæ are simpler. It might be pointed out that, for distribution lines, the necessity of strictly accurate computations is nowhere near as great as it is with long span transmission lines. Usually, comparatively rough methods are used for determining sags in the field, insulator ties allow considerable creepage of the wire, adjusting differences in adjacent spans. These and other similar factors make great accuracy of computation of little value. The sags specified for field use should be as simple and "workable" as possible and yet be as near as practicable to theoretically correct amounts.

Parabolic Formula.—The simple parabolic formula giving the relation between sag, tension, and span is as follows:

$$d = \frac{w_1 L^2}{8T}, \tag{87}$$

where

d = deflection in feet in plane of the resultant load.
w_1 = resultant load in pounds per foot.
L = span in feet.
T = tension in the wire in pounds.

For long spans the above is not accurate as to the value of T since T really represents the *horizontal component* of the maximum tension in the wire and where the span is long and the sag large the horizontal component,

$$H = \sqrt{T^2 - (w_1 x_1)^2} \tag{88}$$

where $x_1 = \frac{1}{2}$ the length of the wire in the span but may be taken as approximately equal to one-half the span. The maximum tension T is at the point of support where the conductor is at an angle to the horizontal whose tangent is $w_1 x_1/H$.

The length of the wire in the span is given by the formula

$$l = L + \frac{8d^2}{3L}. \tag{89}$$

These formulæ as given are useful only when dealing with one specific condition of loading and temperature. They do not provide for the determination of sags and tensions if loading or temperature changes from one value to another. If the temperature rises, for example, the wire expands and increases in length. This increase in length results in an increase in sag which in turn reduces the tension in the wire. If the tension is lessened, the elongation of the wire due to tension is also lessened and hence the sag decreased. If the loading on the wire is increased, the tension is increased and hence the elongation increased. This increases the sag which in turn decreases the tension. The composite effect of such changes as these is not a simple matter to determine. Under the "Catenary Method" an accurate means of determining this is described. With the parabolic method an approximate computation as given below will ordinarily be sufficient.[1]

1. Compute length of wire l as shown above for the original condition for which the sag and tension are known.

2. Compute the elongation due to the assumed increase in temperature from the formula,

$$\text{Elongation} = l \propto t, \tag{90}$$

where

$\propto$ = temperature coefficient of expansion (see Table XIX).
t = increase in temperature from that originally assumed.

3. Assume a tension for the final condition and compute the change in length due to change in tension.

$$\text{Change in length} = \frac{T_1 - T_2}{aE} l, \tag{91}$$

where

T_1 = original tension.
T_2 = final assumed tension.
a = cross-sectional area.
E = modulus of elasticity.

4. Add the results of (2) and (3) algebraically to the length determined in (1) and determine the corresponding tension from the parabolic formula given above. If this checks with T_2 the result is correct, if not, a second approximation should be made in (3).

Catenary Method.—The catenary formulæ giving the relation between sag, tension, loading and span are as follows (see Fig. 229):

[1] "Overhead Systems Reference Book," p. 324

Let

$x_1 = \frac{1}{2}$ the span length $= \frac{1}{2}L$.
$w_1 =$ loading in pounds per foot of wire.

$$Y = \frac{C}{2}\left(e^{\frac{x_1}{c}} + e^{-\frac{x_1}{c}}\right) = C \cosh \frac{x_1}{c}. \tag{92}$$

$$\text{Deflection} = d = Y - C;\ C = Y - d \tag{93}$$

$$\text{Length} = l = 2\frac{C}{2}\left(e^{\frac{x_1}{c}} - e^{-\frac{x_1}{c}}\right) = 2C \sinh \frac{x_1}{C}. \tag{94}$$

$$\text{Maximum tension} = T = w_1 Y;\ Y = \frac{T}{w_1}. \tag{95}$$

$$\text{Horizontal tension} = H = w_1 C. \tag{96}$$

$$\text{Average tension} = \frac{T + H}{2}. \tag{97}$$

$$(e = 2.7183)$$

These give the relations for a single condition of loading and temperature. The most common problems in the study of sags

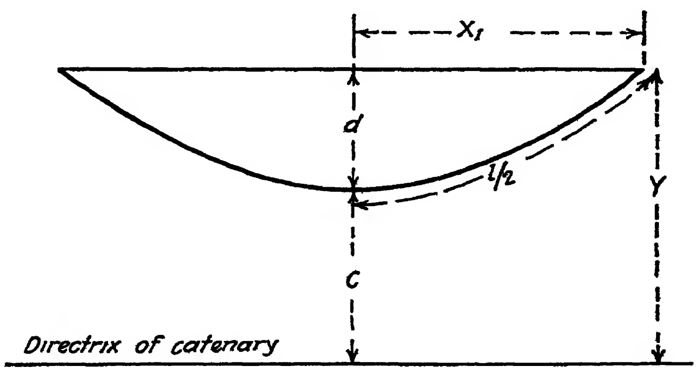


FIG 229.—Catenary.

require the determination of what the sag and tension will become when the loading and temperature have changed somewhat from those originally assumed. For example, for a given conductor the maximum allowable tension T may be known and it is desired that this be not exceeded under the heaviest probable loading conditions. In heavy-loading territory, these conditions are usually assumed to be $\frac{1}{2}$ in. radial thickness of ice, 8 lb. per square foot wind pressure, and 0°F. temperature. The deflection

d corresponding to this loading is readily determined from the above formulæ However, it will also be necessary to find out at what sag and tension the conductor must be installed in order to reach the proper sag when loaded, installation conditions being with no ice or wind loading and probably at a higher temperature.

In making such a determination it is necessary to remember two fundamentals:

1. The wire is an elastic material and hence varies in length with the tension. If the tension is increased, the length is also increased. For homogeneous materials such as copper or steel this increase is practically in direct proportion to the tension up to its elastic limit as was explained previously in this chapter. The proportion is expressed by the modulus of elasticity.

$$\text{Elongation per unit length} = \frac{\text{stress in pounds per square inch}}{E}.$$

For composite materials such as steel-reinforced aluminum the relation is not so simple.

2. The wire varies in length with the temperature, increasing practically in direct proportion to the rise in temperature if of homogeneous material such as copper.

$$l_t = l_0(1 + \alpha t),$$

where

l_0 = initial length.
l_t = length at temperature $t°$ above initial temperature.
α = temperature coefficient of linear expansion.

A graphical method of arriving at the solution of the combined effect of the various forces acting on the wire was described by Percy H. Thomas[1] and is called the "Thomas chart." Other methods of reaching similar results by computation have been also brought out and are probably more accurate for long spans due to the limitations of graphical solution, but for distribution lines the Thomas chart will be found convenient and sufficiently accurate for practical purposes. The theory of the chart and its use is as follows:

1. A span 1 ft. long is assumed with supports on the same level. The weight of the wire (including any loading it may have) is assumed to be 1 lb. per foot of length. Using the catenary for-

[1] *Proc.* A.I.E.E., Vol. XXX, p. 1131, 1911.

mula, the deflection and length of the wire are computed for various maximum tensions in the wire and plotted as shown in Fig. 230.

In order to make this curve applicable to spans of any length and any amount of loading the ordinates, instead of representing merely the tension in the 1-ft. span, with unit loading, may be considered as representing a *stress factor* equal to the maximum tension in the span used, divided by the length of span and by the loading in pounds per foot. The curves may be shown to be mathematically correct for this assumption.

$$\text{Stress factor} = \frac{T}{w_1 L}.$$

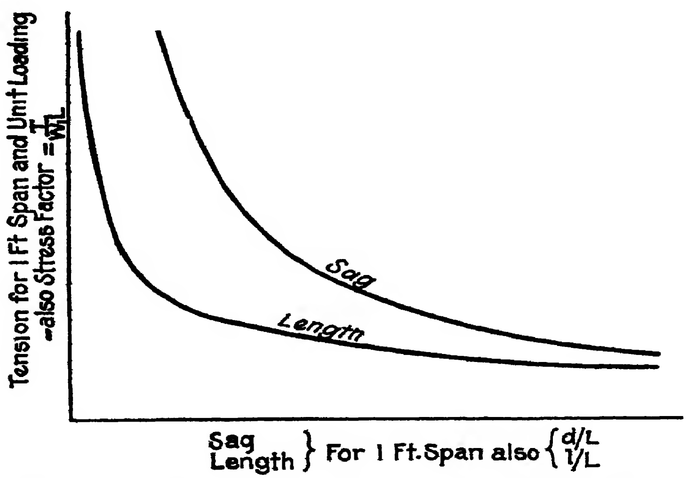


FIG. 230.—Sag-length curves for 1-ft span, loaded with 1-lb. per foot.

Using the same symbols as given previously, the deflections and lengths are given as deflections and length *per foot* of span and total values are obtained by multiplying by span length.

Table XXXIV gives the figures used in plotting this chart.

This chart then will give the deflection and length of the wire in any given span for any condition where the maximum tension is assumed and the loading is known—the same as may be obtained from the fundamental catenary formulæ given above or approximately from the parabolic formula.

2. The elastic curve of the wire may be plotted on a chart of similar coordinates. This curve is assumed to be a straight line up to the elastic limit of the material. If, for example on

TABLE XXXIV.—DATA FOR PLOTTING THOMAS' CHART

Stress factor	Sag in feet per foot span	Length per foot span
0 8965	0 18226	1 083691
0 9879	0 15455	1 061089
1 0501	0 14100	1 051185
1 1276	0 12763	1 042191
1 2255	0 11441	1 034093
1 3513	0 10134	1.026881
1 5170	0 08840	1 020542
1 7422	0 07556	1 015068
2 0628	0 06283	1.010444
2 5502	0 05017	1.006680
3 3709	0.03757	1 003754
4 1967	0 03004	1 002402
4 5730	0 02753	1 002017
5 0250	0 02502	1 001668
5 5781	0 02252	1 001351
6 2700	0 02001	1 001066
7 1604	0 01751	1 000817
8 3483	0 01500	1 000599
10 0125	0 01250	1 000417
12 5100	0 01000	1 000266
16 6742	0 00730	1 000150
20 0063	0.00625	1 000104
25 0050	0.00500	1 0000667
28 5758	0.00438	1 0000511
33 3371	0 00375	1 0000372
40 0031	0 00313	1 0000261
50 0025	0.00250	1 0000167
52 6339	0 00238	1.0000151
55 5578	0 00225	1 0000136
58.8257	0 00212	1 0000118
62 5020	0 00200	1 0000107
66 6685	0 00188	1 0000094
71.4303	0.00175	1 0000082
76 9247	0 00162	1 0000071
83 3348	0 00150	1.0000061
90.9105	0 00138	1 0000051
100.0013	0 00125	1 0000042

Fig. 231, the tension is such that the length is l_1 ft. when the wire is stressed, if the stress is removed the wire will shorten to an unstressed length of

$$l_0 = l_1\left(1 - \frac{T/a}{E}\right). \tag{98}$$

The line m is the elastic curve of the wire, representing the elongation as the stress increases.

If now, the ordinates are assumed to be in terms of *stress factor* or T/w_1L_1, the line represents the elastic curve of the wire corresponding to the loading w_1. That is, for a given span and a given loading w_1, the line describes the increase in length of wire per foot of span, as the maximum tension T increases.

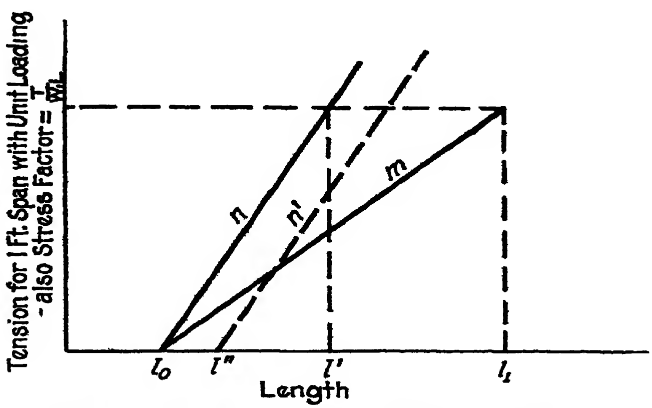


FIG. 231.—Elastic curves for different loadings.

If the load is changed to some other amount, w_2 lb. per foot, the elastic curve corresponding to the new loading will be a different line. Assuming, for example, that $w_2 = \frac{1}{2}w_1$. If the same stress factor is used as before, the tension T_2 must be one-half as much as it was with w_1, since the stress factor $= T_1/w_1L_1 = T_2/w_2L_2$. The increase in length from l_0 to l' when T_2 is applied will be one-half the increase to l_1 when T_1 was applied. Therefore, the second line n represents the elastic curve of the wire corresponding to the load w_2.

3. The length curve on Fig. 230 gives, for any stress factor, the length of the wire due to its being hung up in a catenary shape in the span. The elastic curves on Fig. 231 give, for any stress factor, the length of the wire due to the tension in it. The point where these two curves intersect, if plotted on the

same chart, see k, Fig. 232, is the only point where the length of the given wire in the span corresponds to the stressed length of the same wire under the same tension. That is, for any less tension, the natural stressed length of the wire would be shorter, while the length of the wire in the span would be longer in order to make up for the increased sag corresponding to that tension. For increased tension the reverse would be true. The intersection is the only point which satisfies both conditions.

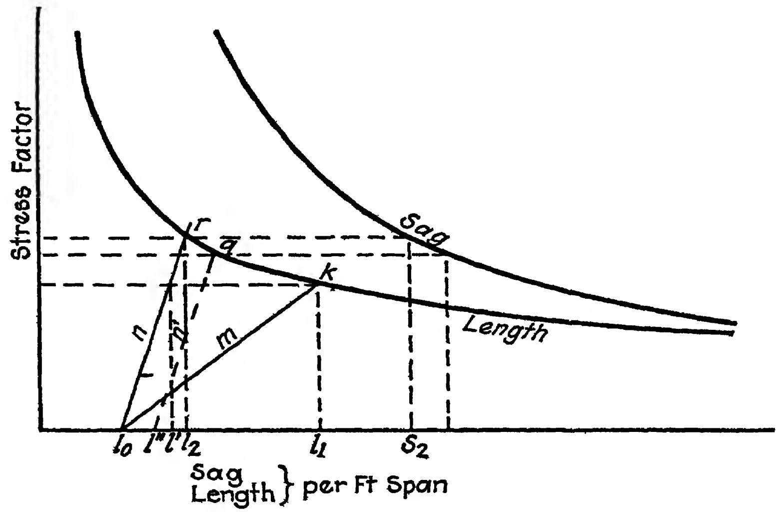


Fig 232.—Thomas chart.

It is apparent, therefore, that if for w_1 and the stress factor assumed, the length is l_1 and the corresponding unstressed length is l_0, if the loading is changed to w_2, the only point for which the length will satisfy both the span curve and the elastic curve will be at the intersection of the elastic curve for w_2, n, with the span curve at the point r. The abscissa of this point, l_2, gives, therefore, the length of the wire when the loading has changed from w_1 to w_2.

The ordinate of the point r is the corresponding stress factor and from it may be obtained the tension in the wire for the new loading.

$$T_2 = w_2L \times \text{Stress Factor}.$$

The corresponding sag S_2 is obtained from the sag curve with the same stress factor.

By the above method, therefore, it is possible to start with any assumed loading and tension, such as the maximum allowable tension with ice and wind loading, determine the sag and length of the wire at that loading, and proceed therefrom to any other loading w_2, such as the weight of the wire without wind or ice, determining the sag and tension under those conditions.

4. If the temperature changes, the unstressed length l_0 will change. Assume the temperature rises $t°$ from that for which the elastic curve in Fig 231 was determined. The unstressed length will change from l_0 to l''.

$$l'' = l_0(1 + \alpha t). \tag{99}$$

If the loading w_2 remains the same, the elastic curve will be a line n' parallel to n, passing through l''. Transferring this to Fig. 232, the point q where n' intersects the span curve determines the length, tension, and sag for the new temperature. This operation may be similarly carried out for any desired temperature and loading.

This is a detailed explanation of the theory underlying the Thomas chart. Brief directions for using the chart will now be given. Table XXXIV gives values from which the chart may be plotted. On account of the great variety of problems met with in practice, it is usually necessary, in using the chart extensively, to plot it to several different scales (both horizontal and vertical) and on as large a scale as convenient, leaving space to the left of the origin for lengths less than 1, which are often encountered. Figure 233 shows the chart in one form and an example is carried through the instructions given and indicated on the chart.

Use of Thomas' Chart.—Instructions and example will be given, starting with heavy loading and low temperature and passing to lighter loading and higher temperature. The principles given can be easily followed in reverse direction, however, if well understood.

1. Assume the span, size of conductor, maximum assumed loading, and maximum allowable tension at that loading are known. The stress factor is then computed, stress factor $= T/w_1L$.

Example.—150 ft., span, No. 0 T.B. weatherproof, copper, medium hard drawn.

Maximum tension . . . . 1,600 lb.

Load per foot with ½ in ice, 8 lb. wind,

$$w_1 = 1.542.$$

$$\text{Stress factor} = \frac{1{,}600}{1.542 \times 150} = 6.92$$

From the chart, sag = 0.0182 per foot span, . . . × 150 = 2.73 ft total.

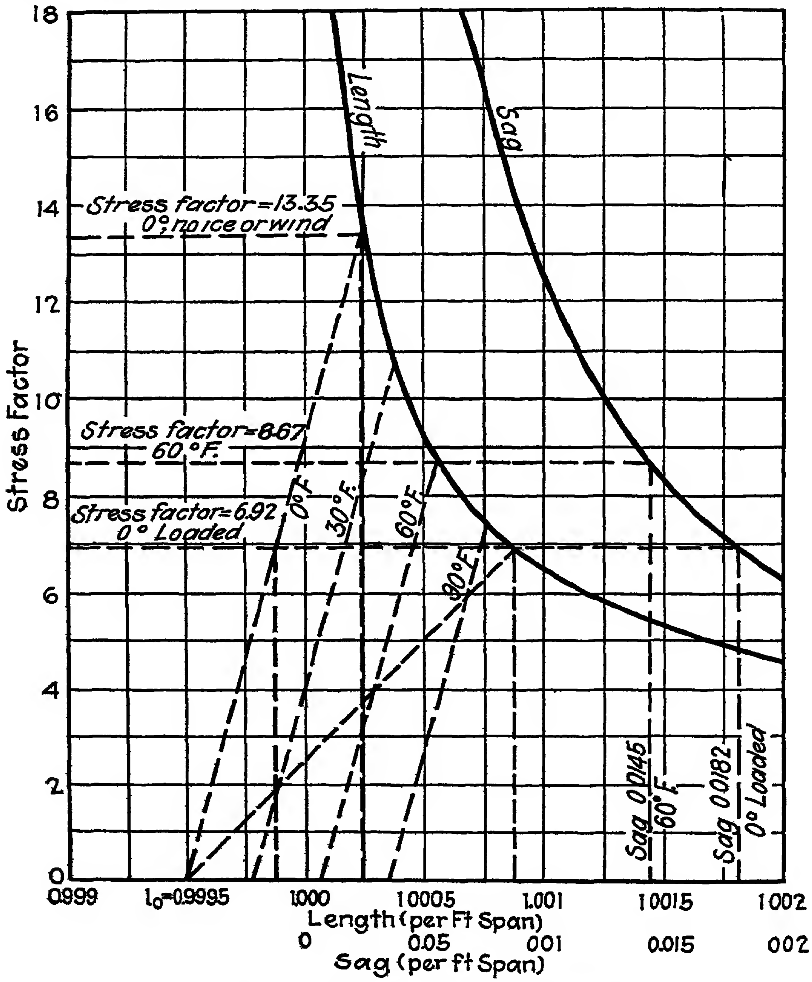


FIG. 233.—Thomas chart with example.

Length = 1.00088 per foot span, . . . × 150 = 150.132 ft. total.

2. Compute the unstressed length from the length found, using the formula,

$$l_0 = l_1\left(1 - \frac{T}{aE}\right). \tag{98}$$

Draw the elastic curve for w_1.

Example.—$E = 14 \times 10^6$
$a = 0\ 0829$

$$l_0 = 1\ 00088\left(1 - \frac{1{,}600}{0\ 0829 \times 14 \times 10^6}\right) = 1.00088(1 - 0\ 00138)$$

$= 0.99950$ per foot span.

3 For any other desired loading, such as that due to the weight of the wire only, compute the length for the same stress factor as used for w_1, the tensions being $l' = l_0 + \frac{w_2}{w_1}(l_1 - l_0)$

Locate the intersection of the ordinate through l' and the stress factor abscissa used in (1), and through that point and l_0 draw the elastic curve for loading w_2.

Example.—$w_2 = 0\ 424$

$$l' = 0\ 99950 + \frac{0\ 424}{1.542}(1\ 00088 - 0\ 99950)$$

$$= 0.99950 + 0\ 00038 = 0.99988 \text{ per foot span}$$

4 Where this line intersects the *length* curve is the point whose ordinate is the stress factor for the new loading condition and whose abscissa is the length for that condition.

Example.—$l_2 = 1.00023$.

Stress factor for $w_2 = 13.35$.

Tension = stress factor $\times w_2 \times L = 13.35 \times 0.424 \times 150 = 850$ lb.

Sag = 0 0094 per foot span = 1 41 ft total

5. For a higher temperature condition, the loading remaining w_2, compute the increased unstressed length l'' from the formula

$$l'' = l_0(1 + \alpha t). \tag{99}$$

Locate l'' on the base line and draw the elastic curve for that temperature through it, parallel to the elastic curve for w_2 through l_0, as determined in (3). Where this intersects the length curve is the point whose ordinate is the stress factor for that temperature and loading and from which the tension and sag may be determined

Example.—Assume the original temperature 0°F.

Temperature coefficient, $\alpha = 9.5 \times 10^{-6}$.

For 30°F., the unstressed length will be

$$l_{30} = l_0(1 + 30\alpha) = 0.99950(1 + 0.000285) = 0.999785.$$

Stress factor for 30°F. = 10.62.

$$T_{30} = 675 \text{ lb}$$

$$\text{Sag}_{30} = 0.0118 \times 150 = 1.77 \text{ ft}$$

For 60°F.,

$$l_{60} = 1.000070.$$

$$\text{Stress factor}_{60} = 8.67.$$

$$\text{Sag}_{60} = 0.0145 \times 150 = 2.18 \text{ feet.}$$

For 90°F.,

$$l_{90} = 1.000354.$$

$$\text{Stress factor}_{90} = 7.42.$$

$$\text{Sag}_{90} = 0.0169 \times 150 = 2\ 54 \text{ ft.}$$

This method is applicable to any type of conductor whose elastic curve approximates a straight line for the range of values being used. The general theory may be also applied, with some variations, to other materials, such as steel-reinforced aluminum as will be described later.

Supports at Different Elevations.—When the supports of the span are at different elevations, the low point of the span will of course occur at a point between the center of span and the lower support. Under certain conditions, the low point might fall beyond the lower support, that is, there will be an uplift at that support. This is to be avoided. As the loading and temperature changes, the low point will move horizontally along

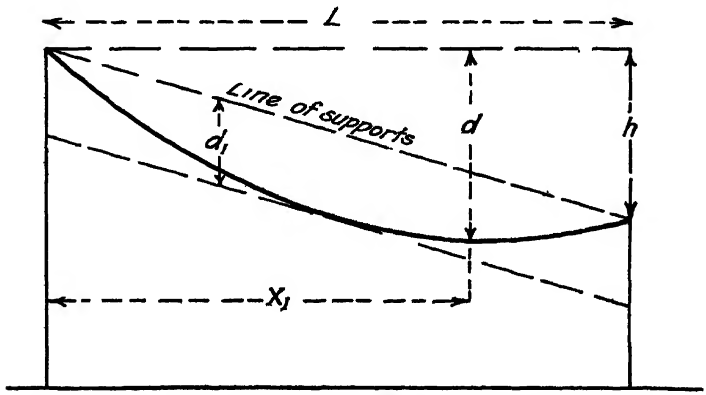


FIG. 234.—Span with supports at different elevations.

the span and it is a somewhat difficult problem to compute for this accurately. For distribution spans it will usually be sufficiently accurate to assume that this point remains fixed. The sags and tensions are then obtained assuming a half-span between that point and the upper support (the sag or deflection being measured from a horizontal line through the upper support). The location of the low point may be approximated from the formulæ

$$x_1 = \frac{L}{2} + \frac{hT}{Lw_1} \tag{100}$$

or

$$x_1 = L\frac{\sqrt{d}}{\sqrt{d-h} + \sqrt{d}} \tag{101}$$

where h = the difference in elevation of the two supports,

x_1 = the horizontal distance of the low point from the

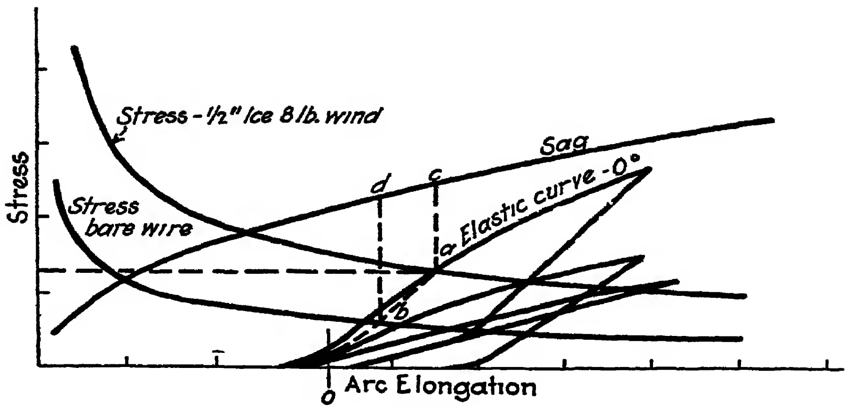
upper support. In solving the problem after x_1 is determined, the length of span when used must be $2x_1$ and not L.

For practical purposes, in sagging-in the conductor in the field, it is sometimes convenient to determine the sag as the vertical deflection from a line through the points of supports, d_1, Fig. 234. This may be closely approximated by computing the sag as if the supports were on the same elevation and the span lengths were L.

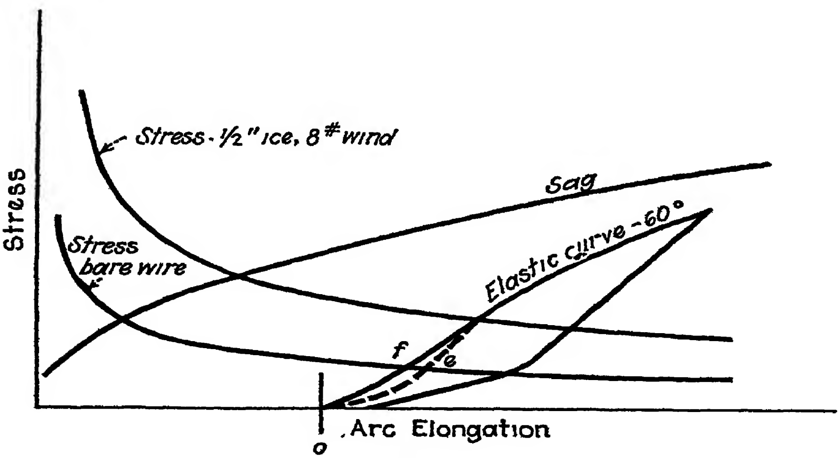
Sags for A.C.S.R.—A method of determining sags for steel-reinforced aluminum has been brought out by Theodore Varney of the Aluminum Company of America. In fundamental principle it is similar to the Thomas method with the exception that allowance is made for the fact that the elastic curve is not a straight line. The elastic curve is determined by actual test for any size of conductor and this applied in obtaining sags at various loadings and temperatures, the composite temperature characteristic of the material also being recognized. The method cannot be given in great detail here. In fact, for complete computation, the elastic curves of all the sizes of wires used must be known. These can be approximated for preliminary calculation if desired, however, from the known characteristics of the component materials and the proportion of each used. The method is, briefly, as follows:

1. The elastic curve of the wire to be used is obtained by test for stresses up to the "working limit" (about 70 per cent of the ultimate strength) and for some given temperature such as 60°F. This is plotted as shown in Fig. 235 (*a*). This is done on transparent paper. The elastic curves of the steel and aluminum components are also obtained by test, their ordinates summing up to that for the whole wire at any elongation. The curves give the elongations for both initial stress on the cable and also when that stress is released. For subsequent stressing, the curve is assumed to follow the same path as when initial stress was released. If the wire is stressed only to the point *a*, similar return curves may be made up, the curves for the individual materials drawn from *a′* and *a″* being parallel to those from the "working limit." For the composite wire, the curve is obtained from the sum of the ordinates of the aluminum curve and the steel curve.

2. The curves on Fig. 235 (*a*) are converted to any other desired temperature such as 0°F., by computing and applying the



(d)



(e)

FIG. 235 —Sag charts for A C S R. (a), elastic curves—combined cable, 60° F ; (b), elastic curves—combined cable, 0° F., (c), A.C.S.R.—span chart; (d), combination of elastic curves and span chart, 0° F.; (e), combination of elastic curves and span chart, 60° F

reduction in length of each component, steel and aluminum, separately, drawing their individual curves, then obtaining the combined curve for the wire as a whole by adding these component curves together. Figure 235 (b) shows this operation. It should be plotted on transparent paper.

3. The span curves for the wire in question and for the particular span being studied are plotted from the catenary formulæ for several different loadings such as for bare wire, for ½ in. ice

and 8 lb. wind, for ½ in. ice and no wind, etc. The coordinates used are *pounds per square-inch tension* and *elongation of the arc length in percentage of span length,* the same scale being used as in the elastic-curve charts. Figure 235 (*c*) illustrates this curve. It gives corresponding tensions, sags, and elongations in the wire in the catenary span for the different loadings.

4. Assume for example that a maximum stress in pounds per square inch is established for the wire. It is desired that this be not exceeded at 0°F. and loading of ½ in. ice, 8 lb. wind. The elastic curves for 0°F., Fig. 235 (*b*), are placed over the span curves, Fig. 235 (*c*), with their base lines coinciding, and the chart is moved horizontally until the elastic curve for the wire crosses the span curve for the ½ in. ice, 8 lb. wind, loading at the ordinate equal to the assumed tension (the point *a*, Fig. 235 (*d*)). The intersection of the ordinate through this point with the sag curve "*c*" gives the sag in the span for this condition.

Elastic curves for released stress are drawn for this point *a* in the manner indicated on Fig. 235 (*a*). If it is desired to obtain the tension for bare wire (at 0°F.) this is given by the ordinate of the point *b* where this curve intersects the span curve for bare wire. The ordinate through this point intersects the sag curve at the point *d* from which the sag for this condition is obtained.

5. To obtain the sag and tension at 60°F., the curves of Fig. 235 (*a*) are used. This is placed over the span-curve chart, Fig. 235 (*c*), with its origin coinciding with that of the 0°F. chart, Fig. 235 (*b*), as located in (4) above. The intersection of the elastic curve of the cable with the span curve for bare wire is a point *e* whose ordinate is the tension for that temperature and through which an ordinate intersecting with the sag curve gives the sag, see Fig. 235 (*e*).

6. If the wire has not been stressed by heavy loading, the curve of initial stress instead of subsequent stress after loading should be used. This will give the intersection at the point *f* from which sag and tension can be obtained. These will be quite a little different from the values after the wire has been stressed and released.

Sag Tables.—It is not within the province of this book to give complete tables of sags and tension for the various sizes and kinds of wires used as conductors. Such tables may be found in the National Electrical Safety Code and elsewhere. The "Overhead

System Reference book"[1] gives a number of charts indicating sags.

A short table is given, however, illustrative of a practical sag table which has been used for construction of distribution lines on a certain system in heavy-loading territory. Where various sizes of wires are used together, it is preferable to give them about the same amount of sag if practicable. Hence, the sags in this table were chosen so that the smaller wires would not be overstressed, the sags for larger wires being greater than would be necessary if they were used alone. It is applied to all sizes of medium-hard copper, T.B.W.P., under all grades of construction, except No. 6 under Grades A and B (Safety Code), for which the sag must be increased.

TABLE XXXV.—SAG, IN INCHES IN CENTER OF SPAN MEDIUM-HARD-DRAWN COPPER WIRE T B W.P.

Span, feet	Temperature (Fahrenheit)					
	0°	20°	40°	60°	80°	100°
75	4	4	4	5	7	8
100	5	7	10	12	15	17
125	9	12	15	18	21	24
150	17	20	24	27	30	33
175	25	29	33	36	39	43

Splices and Taps.—Any joints made in conductors, either in splicing two ends together or in tapping one off the other, should, for best results, be of such a nature that no additional resistance is introduced into the circuit. In addition they should be permanent, *i.e.*, not subject to damage by corrosion or by the mechanical stresses or movements to which the conductors are subject. For splices, mechanical strength is a feature of major importance, and should be practically as great as that of the conductor itself.

Several ordinary types of splices are shown in Fig. 236. The sleeve splice is quite generally used for medium-hard and hard-drawn wires, since it is mechanically strong and does not require soldering which is likely to anneal and weaken such materials. It is also used for aluminum and A.C.S.R. conductors, since these cannot be successfully soldered on the field. The sizes for which the sleeve can be used is limited to about No. 0000.

[1] N.E L A.

For larger sizes of copper, the stranded-wire splice shown is used; for aluminum, special joints are provided. The solid-wire splice is generally used for soft-drawn conductors and should be soldered to increase conductivity and prevent corrosion.

For taps, conductivity is the main requirement, large mechanical strength being not necessary in most cases. Several types of taps are shown in Fig. 237. The served tap is probably the commonest for copper wire. The wrapped tap is suitable for the larger sizes or very stiff wires which cannot be readily served.

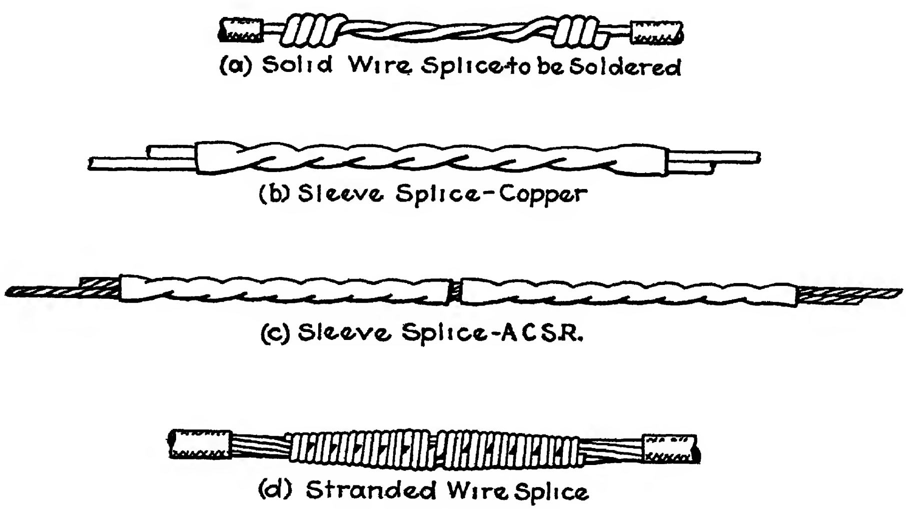


Fig. 236.—Splices.

The stranded-wire tap is for the large sizes of stranded wire. All of these should be soldered. Taps where aluminum wire is concerned must be made with some form of clamp. One with two or three bolts is to be preferred to a one-bolt clamp as a rule. For use, where the tap involves one aluminum and one copper wire, aluminum clamps with copper bushings are available. Similar clamps of bronze or copper are sometimes used for copper-to-copper taps.

Small clamps or so-called "solderless connectors" are used to some extent for tapping off service wires from secondary mains. They are claimed to reduce cost by eliminating the soldering. Some care must be used in selecting such a connector to obtain one which will not itself corrode in a few years, will maintain the joint tight, and of low resistance after several years of vibra-

tion, etc., and which is of such a shape and size as can be readily handled and installed. Several types are available but they have not as yet come into general use

On covered or insulated wire, the splice or tap is usually covered or insulated in such a way as to make the covering at that point

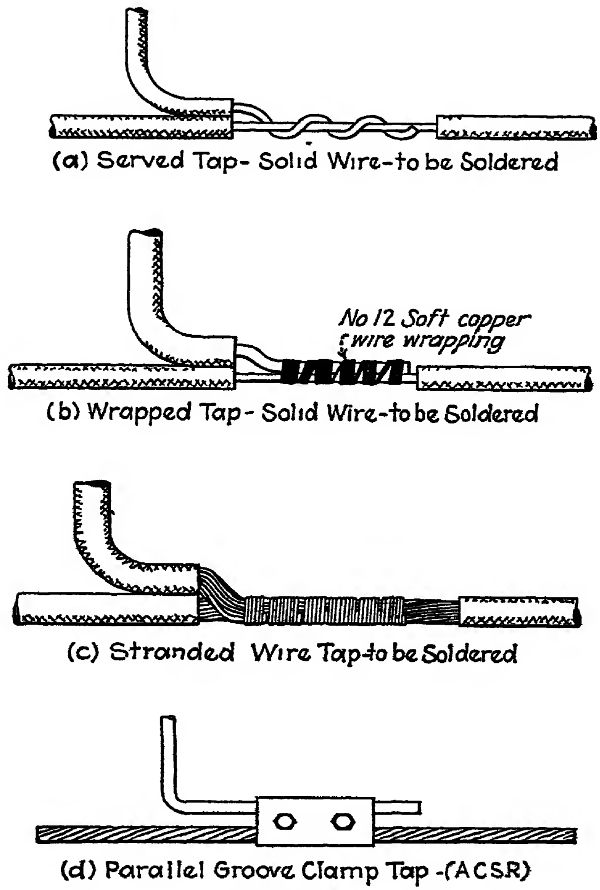


FIG. 237.—Taps.

equivalent to that of the rest of the wire. Friction tape is commonly used on weatherproof wire. On insulated wire, rubber tape should be applied as an insulation, covered with friction tape.

Ties.—Ties for attaching conductors to their insulators should be mechanically strong enough to prevent the conductor being

pulled off the insulator under stress but should, at the same time, have some flexibility. For poles where no dead-end stress is to be carried, it is sometimes preferable that the tie be such that the wire will slip through somewhat under unusual stress, such as a broken wire on one side, rather than breaking the pin.

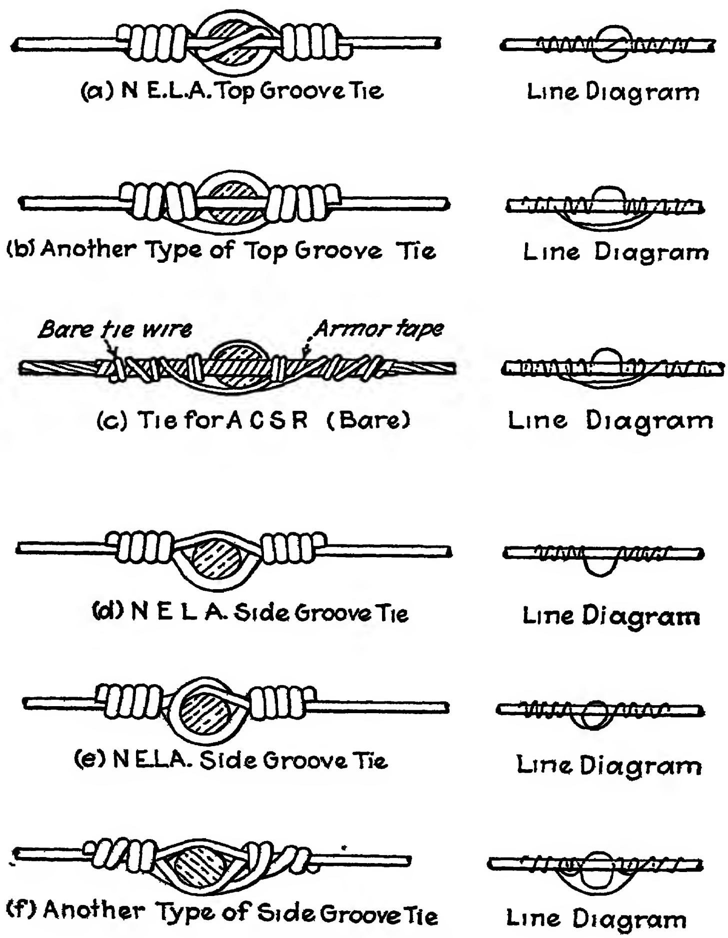


Fig. 238.—Ties.

For bare copper wire, bare soft-drawn copper is suitable for tie wire. For weatherproof wire, weatherproof tie wires are generally best. For aluminum or A.C.S.R., soft-drawn aluminum is preferable. The size of the tie wire is somewhat optional but should as a rule be large enough for the mechanical strength

desired (depending on the size of conductor held) and small enough to be easily served up. The "Overhead Systems Reference Book"[1] gives the following sizes which may be used as a guide:

For No. 6 conductor	No. 6 tie
For No 4 conductor	No. 6 tie
For No. 2 conductor.	No. 4 tie
For No. 0 conductor .	No. 4 tie
For No. 00 and larger	No. 2 tie

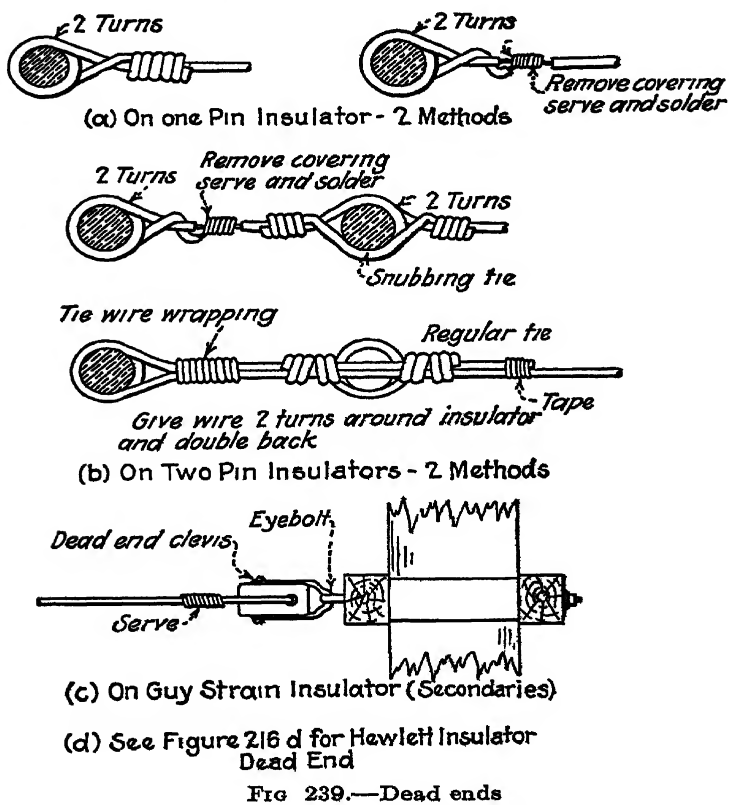


FIG 239.—Dead ends

Figure 238 shows several forms of ties which have been found suitable. On the aluminum, an armor tape is used to increase the size of the wire to protect against burning by flashover and to prevent breaking due to crystallization under movement of the wire.

[1] N E.L.A

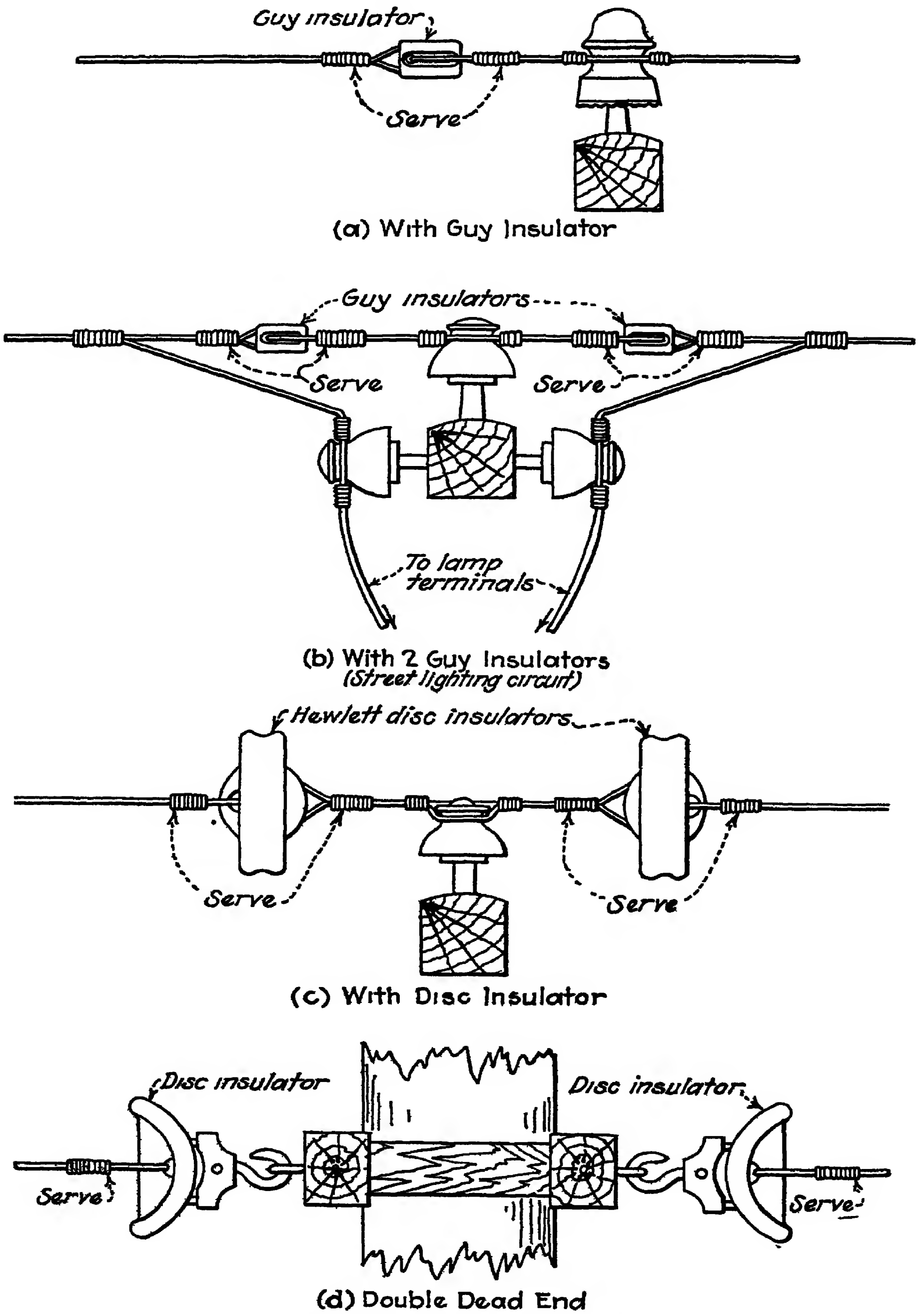


FIG. 240.—Cutting circuits.

Dead End.—Where a conductor is dead ended, its tension must be held and transferred to the supporting members. Two methods of dead ending are commonly used. Small wires are often dead ended on pin insulators, being held by being passed around the insulator and tied in some manner. Large wires are more often dead ended in strain insulators.

Figure 239 illustrates the method of attaching and holding the wire on several types of dead ends.

Figure 240 shows methods of cutting a circuit electrically where the structure is mechanically continuous.

CHAPTER XXIII

CLEARANCES

Since overhead conductors are usually not effectively insulated by any covering on the wire itself for the voltage which they carry, it is necessary for the safety of the public, for the safety of workmen working on and around the conductors, and to provide against an undue number of interruptions to service, that certain clearances be maintained between conductors, between conductors and ground, etc. Just what those clearances should be may be open to question and will depend considerably on the conditions of the case such as voltage, number of wires involved, location, probable loading, and similar factors. The National Electrical Safety Code recommends minimum clearances for most of the cases which will usually be encountered. They are the best standard which we have at present on which to base the design of distribution lines.

It should be remembered in studying the question of clearances that there is, or should be, a logical reason for each minimum clearance specified. When establishing a clearance or changing one already established, the reasons for that clearance should be kept clearly in mind and used as a basis for the measurement used rather than allowing it to be determined by a saving in cost or desire to make it fit in with some proposed design. A few of these reasons will be given briefly.

Clearance above ground is for the purpose of preventing anything which may ordinarily pass under the line from coming too close to or in contact with it. In case of a crossing over a country road, sufficient height must be provided to care for the highest vehicle probable, such as a load of hay with a driver standing on top. The same provision should usually be made over driveways coming from fields along the road. For a city street, hay loads are not usual, but large trucks, such as moving vans, are. Also steam shovels, trenching machines, and similar outfits sometimes reach considerable height. Over railroad tracks, not only must freight cars with men on top be considered, but in some cases unusual clearances are desirable to provide for cranes

with high booms which may pass frequently. Where pedestrians only can pass under a line, it is only necessary to get it beyond their reach but it must be remembered that that reach can easily be extended with a cane or similar object. In the extreme case, for example, it may be well in crossing some streams to consider the height to which a fish line might be whipped by a passing fisherman. On large streams, of course, the masts of boats, ice boats, and sometimes derrick scows must be cleared.

Clearance between wires and from wires to their supports is necessary to provide room for workmen to handle them safely while the voltage is on and to pass them to reach other wires. In addition, for the higher voltages they must be far enough apart in the span so that they will not whip together in the wind, causing short circuits.

Clearance above and alongside buildings is for the purpose of preventing unauthorized persons from readily reaching the wires while standing on the roof or leaning from a window.

These reasons are examples of what should be considered in establishing any clearance. It might be said that the avoidance of accidents or interruptions to service by providing ample clearance is usually a real economy even if some additional line cost is involved. It is not a case, however, of where "a little is good, more is better," since the provision of greater clearances than are practicably necessary may involve unwarranted expenditures. Good judgment and experience are essential factors in this matter.

The more important clearance requirements of the Safety Code will be given in the following tables with some brief comments on their application. The Safety Code contains quite a few exceptions to the general rules stated, but for the most part these will be omitted here, as they quite often apply to existing construction or to higher voltages than are usually dealt with on distribution circuits. It is recommended that the operating engineer make a thorough study of the Safety Code, including all these exceptions, as the data given here cannot be considered complete.

Clearance above Ground (Table XXXVI).—The clearances specified are at 60°F., no wind. For spans over 150 ft. it is provided that the clearance shall be increased 0.1 ft. for each 10 ft. excess over 150 ft.

The clearances required above railroad tracks may be compared with the height of ordinary freight cars which is from 14 to 16 ft.

TABLE XXXVI.—MINIMUM VERTICAL CLEARANCE OF WIRES ABOVE GROUND OR RAILS

Nature of ground or rails underneath wires	Guys, messengers, communication, span, and lightning-protection wires; permanently grounded continuous metal-sheath cables—all voltages, feet	Open supply-line wires, arc wires, and service drops			Trolley contact conductors and associated messenger wires	
		0 to 750 volts, feet	750 to 15,000 volts, feet	15,000 to 50,000 volts, feet	0 to 750 volts to ground, feet	Exceeding 750 volts to ground, feet
Where wires cross over						
Track rails of railroads handling freight cars on top of which men are permitted	(c)27	(c)27	(c)28	30	22	22
Track rails of railroads not included above	18	18	20	22	18	20
Streets, alleys, or roads in urban or rural districts	(f)18	18	20	22	18	20
Driveways to residence garages	10	10	20	22	18	20
Spaces or ways accessible to pedestrians only	(g)15	(h)15	(h)15	17	16	18
Where wires run along						
Streets or alleys in urban districts	(j)18	(j)18	20	22	18	20
Roads in rural districts	(j)15	(j)15	18	20	18	20

(c) This clearance may be reduced to 25 ft where paralleled by trolley contact conductor on the same street or highway.

(f) Where a guy crosses a street or alley in urban districts and the section of guy above the street or alley is effectively insulated against the highest voltage to which it is exposed, up to 7,500 volts, the clearance may be reduced to 16 ft at the side of the traveled way.

(g) This clearance may be reduced as follows:

For guys . . . . 8 ft

(h) This clearance may be reduced as follows

(1) Supply wires (except trolley contact wires) limited to 300 volts to ground . . . . 12 ft

(2) Supply wires (except trolley contact wires) limited to 150 volts to ground and located at entrances to buildings. . . . . 10 ft

(3) Where supply circuits of 550 volts or less with transmitted power of 1,600 watts or less are run along fenced (or otherwise guarded) private rights-of-way in accordance with the provisions specified in rule 220, B, 3 (Safety Code) . . . . 10 ft

(j) Where a pole line along a road is located relative to fences, ditches, embankments, etc., so that the ground under the line will never be traveled except by pedestrians, this clearance may be reduced as follows:

Supply conductors. . . . . 12 ft.

above rail. A man standing on top would therefore bring this to 20 to 22 ft. Considering that the conductors will have greater sag under high temperatures or under ice loading, the clearances given are not unreasonable.

In streets or alleys in urban districts moving vans may reach 10 to 12 ft above the roadway, on county roads, hay loads 10 ft. high with a 6-ft. man on top make 18-ft. clearance not too great. In fact, with much increase in sag at high temperature a greater clearance than 18 ft. is sometimes desirable. For spans greater than 150 ft. this is more or less provided for by the additional clearance required, as stated above.

Clearance of 15 ft. over ways accessible to pedestrians only may seem excessive in many cases. A reduction to 8 ft. for guys is allowed by the code and to 12 ft. for supply conductors where the space underneath is such that it cannot be traveled excepting by pedestrians. The latter qualification may be rather difficult to determine as a certainty however, as places today only accessible to pedestrians may tomorrow be so altered as to be accessible to vehicles. Another consideration is that a good height above ground is some deterrent to the ambitions of mischievously inclined persons who like to see the fireworks when a short circuit occurs and are not averse to assisting therein.

The 18-ft clearance over alleys, without qualification, is likely to be a hardship in many cases however, as it very often occurs that service entrances are made to garages, or other low buildings located on the alley line, from poles across the alley. Even 10-ft. clearance at the entrance point is sometimes difficult to obtain without special construction. Some modification of this would seem reasonable, especially since high vehicles do not often frequent alleys, especially in the residence districts.

Wire Crossing Clearances (Table XXXVII).—The clearances specified are for 60°F., no wind and where the sum of the distances from the point of intersection to the nearest supporting structure of each span is not over 100 ft. If it is over 100 ft., the clearances given should be increased 0.1 ft. for each 10 ft. of excess over 100 ft.

Horizontal Separation (Table XXXVIII).—The pin spacing of the cross-arm in common use[1] is about 14 in. or a little less. As a rule this spacing is satisfactory for voltages up to the order 2,300. For higher voltages, although such spacing may be not

[1] See N.E.L.A suggested standard in Chap XVII.

TABLE XXXVII.—WIRE CROSSING CLEARANCES

(All Voltages Are between Wires Except for Trolley-contact Wires Where Voltages Are to Ground)

Nature of wires crossed over	Communication wires, feet	Open-supply wires 0 to 750 volts and permanently grounded continuous metal-sheath supply cables of all voltages		Open-supply wires and service drops		Guys, messengers, span wires, lightning-protection wires, feet
		Line wires, feet	Service drops, feet	750 to 7,500 volts, feet	7,500 to 50,000 volts, feet	
Communication, including cables and messengers	2	4	2	4	6	2
Supply cables having permanently grounded continuous metal-sheath, all voltages	4	2	2	2	4	2
Open-supply wires						
0 to 750 volts	4	2	2	2	4	2
750 to 7,500 volts	4	2	4	2	4	4
7,500 to 50,000 volts	6	4	6	4	4	4
Trolley-contact conductors	4	4	4	6	6	4
Guys, messengers, span wires, lightning-protection wires, service drops 0 to 750 volts	2	2	2	4	4	2

TABLE XXXVIII.—MINIMUM HORIZONTAL SEPARATION AT SUPPORTS BETWEEN LINE CONDUCTORS OF THE SAME OR DIFFERENT CIRCUITS

Class of Circuit	Separation, Inches
Communication conductors	6
Railway feeders:	
0 to 750 volts, No. 4/0 or larger	6
0 to 750 volts, smaller than No. 4/0	12
750 to 7,500 volts	12
Other supply conductors:	
0 to 7,500 volts	12
For all conductors of more than 7,500 volts add for each 1,000 volts in excess of 7,500 volts	0 4

too close for satisfactory working conditions on the pole, it may be closer than is practicable in the span, especially if the spans

TABLE XXXIX.—VERTICAL SEPARATION OF CROSS-ARMS CARRYING CONDUCTORS

Conductors usually at lower levels	Supply conductors, preferably at higher levels				
	0 to 750 volts and permanently grounded continuous metal-sheath cables of all voltages	750 to 7,500 volts	7,500 to 15,000 volts	15,000 to 50,000 volts	
				Same utility	Different utilities
Communication conductors.					
General	4	4	6	..	6
Used in operation of supply lines	2	2	4	4	6
Supply conductors:					
0 to 750 volts	2	2	4	4	6
750 volts to 7,500 volts. . .	..	2	4	4	6
7,500 volts to 15,000 volts.					
If worked on alive with long-handled tools, and adjacent circuits are neither killed nor covered with shields or protectors.	.	.	4	4	6
If not worked on alive except when adjacent circuits (either above or below) are killed or covered by shields or protectors, or by the use of long-handled tools not requiring linemen to go between live wires.	.	.	2	4	4
Exceeding 15,000 volts, but not exceeding 50,000 volts		.		4	4

are relatively long and the sag considerable. The Safety-Code provision for minimum spacing with relation to sag was given in Chap. XXII under the discussion of sag. It will probably be

found that it is often desirable to exceed those minimums somewhat in practice to prevent trouble from wires whipping together in the wind. A double pinspacing of 28 in. or thereabouts is quite commonly used for distribution voltages over 2,300, in spans up to 175 ft. or so. For longer spans such as 300 ft. even greater spacing than this will sometimes be of advantage.

Vertical Separation.—Table XXXIX refers to separation between cross-arms and this is usually the separation between conductors also. A reduction of 8 in. where the clearance is 4 ft. or less and 12 in. where 6 ft. is allowed between *conductors* in case pin heights are different.

Where conductors are not carried on cross-arms, the same separations are required, except that for voltages not over 750 volts and spans not over 150 ft., conductors carried on racks on the side of the pole may have a minimum separation of 4 in.

Where conductors have different sags, the clearance specified may be reduced not over 25 per cent at the center of the span

Vertical Clearance of Conductors from Equipment.—Between conductors and non-current carrying metal parts of equipment, the clearances required are as follows:

Supply conductors not exceeding 750 volts, to communication equipment . . . . . the 4-ft. separation specified in Table XXXIX may be reduced to 40 in.

Communication conductors, to supply equipment, ... separations given inTable XXXIX as 4 ft. and 6 ft may be reduced to 40 in. and 60 in., respectively. (This is most often applicable to the separation between supply transformers and communication conductors on jointly used poles.)

Span wires or brackets for lamps or trolley-contact conductors:

From cross-arms carrying communication conductors . .	2 ft.
From messenger wires carrying communication conductors	1 ft.
From terminal box of communication cables	1 ft.

Clearance from Supports.

TABLE XL.—MINIMUM CLEARANCE IN ANY DIRECTION FROM LINE CONDUCTORS TO SUPPORTS, AND TO VERTICAL[1] OR LATERAL[2] CONDUCTOR, SPAN, OR GUY WIRES ATTACHED TO THE SAME SUPPORT

Clearance of line conductors from	Communication lines		Supply lines		
	0 to 7,500 volts				Exceeding 7,500 volts add for each 1,000 volts excess, inches
	In general, inches	On jointly used poles, inches	In general, inches	On jointly used poles, inches	
Vertical and lateral conductors					
Of same circuit	3	3	3	3	0.25
Of other circuits	3	3	6	6	0 4
Span and guy wires attached to same pole					
General	3	6	6	6	0 4
When parallel to line	(b)	(b)	(b)	(b)	0 4
Lightning-protection wires, parallel to line	(b)	(b)	(b)	(b)	0 4
Surfaces of cross-arms	3	3	3	3	0 25
Surfaces of poles	3	5	3	d5	0 25

(b) Clearance shall not be less than the separation required by Table XXXVIII between two line conductors of the voltage concerned

(d) This clearance applies only to supply conductors carried on cross-arms below communication conductors on joint poles. Where supply conductors are above communication conductors, the clearance shall be at least 3 in.

[1] By vertical conductors are meant conductors running vertically from one level to another, such as training wires from a circuit on an upper cross-arm to a transformer lower down on the pole

[2] By lateral conductors are meant conductors running horizontally at right angles to the direction of the line, such as a training wire carried from an inner pin position along the face of the arm to be trained down on the ends of the arms, or a service wire carried across a pole.

Climbing Space.—It is obvious that, as a matter of safety and convenience to workmen, a path should be provided up the pole through the wires, through which they may climb without an undue amount of gymnastics. This is especially important where lines of the higher voltages are worked upon while alive.

The Safety Code's provision in this regard makes for safe working conditions. The requirement is for a clear space of the specified dimensions, extending "past any conductors, cross-arms, or other parts," the same dimension being provided both along and across the line. That is, it furnishes a vertical path of square cross-section, free from obstructions, through which a man may climb. The dimensions of the climbing space are given as

For conductors less than 300 volts	24 in
For conductors 300 to 7,500 volts	30 in.
For conductors 7,500 to 15,000 volts	36 in.
For conductors over 15,000 volts	more than 36 in

On jointly used poles, climbing space through communication conductors shall be the same as for conductors immediately above them.

The climbing space should extend straight for at least 4 ft. above and below the conductors in question. Beyond these limits it may shift from one side of the pole to the other. It may be on one corner only. Sections of the pole, or structure, or longitudinal or vertical runs encased in insulating conduit, are not considered as obstructing the climbing space. On buck-arm poles the climbing space should be measured from the face of the buck arm, and will usually require that one or more pin positions on the arms be left vacant. The Safety Code allows a special spacing of 7½ in. between pins under certain conditions to allow for this. The use of a longer arm with normal pin spacing is very often a good solution of this problem, however.

In Fig. 241 are shown several illustrations of climbing space.

Working Space.—Another important provision for safety, convenience, and saving of time in construction is the establishment of an unobstructed working space between conductors at different levels. The Safety Code's stipulation in this regard is that a space free from all lateral or vertical conductors shall be provided, extending from the pole to the outer pin position of the arm and of the same dimension in the other direction as the climbing space, measured from the face of the cross-arm. The vertical height shall be as given in Table XXXIX for vertical distance between line conductors.

Buck arms are likely to obstruct the climbing space. The Safety Code allows a reduction of the working space to 18 in. above each line arm and above each buck arm if no circuits of

voltage over 7,500 volts are involved and the required horizontal clearance between conductors is maintained. This may be accomplished by placing the line arms 36 in. apart on buck-arm poles with the buck arm midway between.

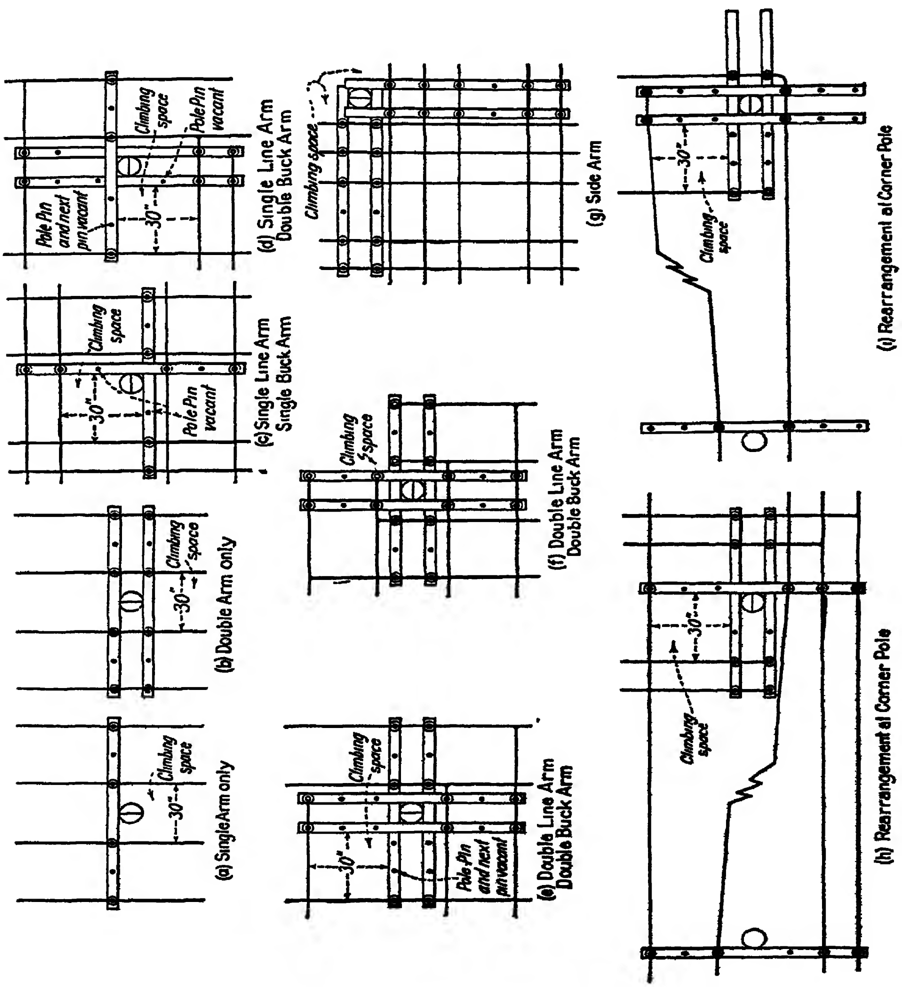


FIG. 241.—Climbing space.

Figure 242 illustrates the requirements for working space.

It should be pointed out that not only are the provision of ample climbing and working spaces on a pole advisable from the standpoint of accident prevention, but they may accomplish a material saving of time in construction and maintenance work.

The work of a lineman on a pole requires, at best, deliberate action and careful attention to details in protecting himself and the circuits he is handling from injury. If in addition he is forced to work in a cramped position and without sufficient room to handle his tools properly, the time necessary for the job is unquestionably extended considerably.

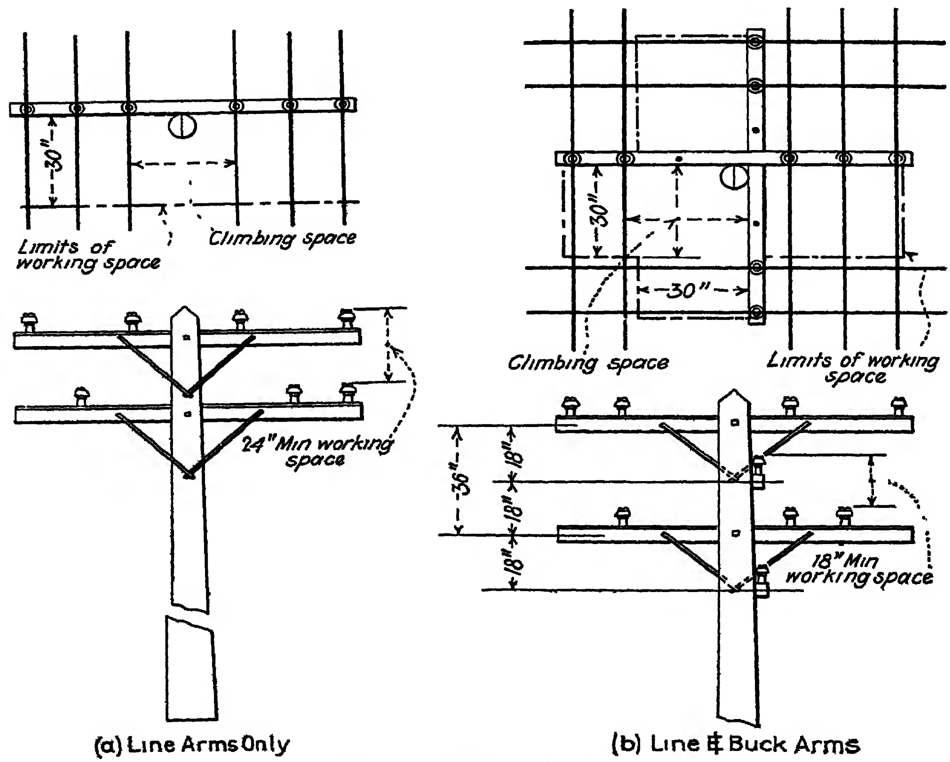


FIG 242.—Working space

Clearance from Buildings.

TABLE XLI.—CLEARANCES OF SUPPLY CONDUCTORS FROM BUILDINGS

Voltage of supply conductors	Horizontal clearance, feet	Vertical clearance, feet
300 to 7,500	3	8
7,500 to 15,000	8	8
15,000 to 50,000	10	10

For voltages over 7,500 volts and spans over 150 ft., increase clearance 0.1 ft. for each 10 ft excess over 150 ft.

There will be many cases where conductors pass buildings where it will be found advisable to increase these clearances, such as where there are balconies, fire escapes, etc., and in passing over flat roofs commonly used by the public. For voltages over 7,500 volts it is stipulated that they should not be carried over roofs of buildings not concerned in the operation of the utility owning the wires

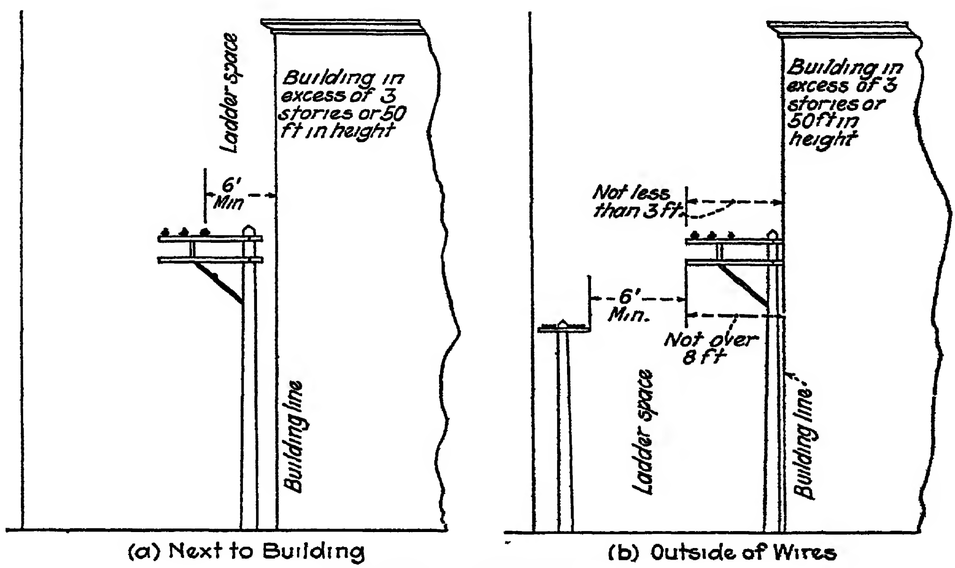


FIG. 243 —Ladder space

Very little is specified concerning voltages less than 300 volts but it is advisable to use some care even with these voltages to keep the wires out of reach of the public, both from a safety standpoint and also to keep them from being disturbed unnecessarily.

In addition to the above given clearances, provision should be made to allow for the raising of fire ladders against the building in case of emergency. The Safety Code stipulates that a clear zone at least 6 ft. wide be left either adjacent to the building, *i.e.*, between it and the wires, or outside the wires, beginning not over 8 ft. from the building. Figure 243 illustrates this requirement.

CHAPTER XXIV

GUYING

In wood-pole line construction, where the loading imposed by the wires is of any considerable amount, its horizontal component is usually sustained by the use of guys. Wood poles themselves are quite limited in strength, for example a Class C pole (see Chap. XVI) has a theoretical ultimate strength of only about 1,600 lb. of horizontal loading applied near its top, Class A poles about 3,300, etc. Even where the pole itself might be sufficiently strong, the setting is likely not to have the stability to develop that full strength. The wire loading at dead ends or at corners or angles of any considerable size will usually be such as to exceed the allowable pole stress and require some additional support. Special structures such as A frames, H frames, push braces, etc. are sometimes employed for this purpose but the most common method is to install guys of steel wire or other high-strength material to take the stress.

The usual assumption in determining the strength of guys necessary for any case is to consider the structure as rigid, the pole acting only as a strut or column under direct compressive stress, the guys assuming the whole horizontal component of the loading. This is the assumption specified in the Safety Code. As a matter of fact, the element of elasticity no doubt plays some part in the distribution of stress in the structure. The guys themselves are of elastic material and when stressed heavily will elongate slightly. Connections at clamps and where the guy is wrapped around the pole are not entirely rigid under stress, anchors are likely to give slightly, etc. All these factors, although perhaps not of great moment in themselves, when combined may serve to alter the assumed condition somewhat, allowing the guyed pole and perhaps adjacent poles to take some of the horizontal stress. For practical purposes, however, the assumption of rigidity is a satisfactory one and on the safe side.

Types of Guys.—Where the wires are carried on cross-arms, the loading is imposed first on the cross-arm and thence transferred to the pole. Under dead-end conditions, if the wire loading is not equally balanced on the arm, *i.e.*, symmetrical about the pole, the unbalance, unless very small, will be likely to twist

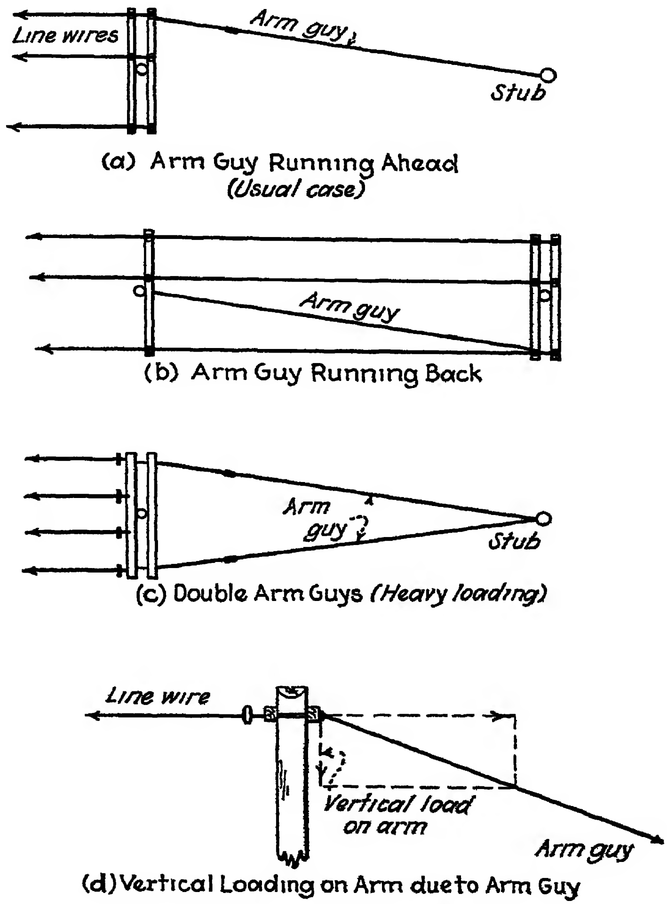


FIG. 244.—Arm guys.

the arm out of position. It may be held in place by using an *arm guy* to take up the unbalance. The arm guy is usually attached to the end of the arm having the heavier load, and carried down to an anchor, or another pole. This is illustrated by Fig. 244 (*a*). Occasionally it may be more convenient, if the strength of the cross-arm permits, to attach the guy to the

other end of the arm and carry it back in the direction in which the load is pulling, Fig. 244 (*b*). Sometimes the load, even though balanced on the arm, may be sufficiently large to overstress the arm unless otherwise supported. In such cases it is necessary to guy both ends of the arm, Fig. 244 (*c*). The strength of cross-arms is discussed in Chap. XVII. It should be remembered in using arm guys that, if they themselves have any considerable angle to the horizontal, they impose a vertical loading on the cross-arm equal to the vertical component of their tension and this loading must be taken into account in considering the strength of the structure, see Fig. 244 (*d*).

Guys sustaining the main stress on the pole are sometimes designated according to the anchorage used as, *pole-to-pole*, *pole-to-stub*, and *pole-to-anchor* guys. Where spans are comparatively short, it is sometimes convenient to carry the guy to the next pole in the line rather than use a separately installed anchorage. Such a *pole-to-pole* guy is illustrated in Fig. 245 (*a*) It is especially adaptable to use where clearance above ground is a requisite, such as where the guy must be carried across a street. It must be remembered in making such an installation that an additional stress is thrown on the pole used for the anchorage, which may overstress it, or at least be undesirable, on account of the tendency to pull the pole out of the vertical. This may be counteracted by further guying of the anchor pole.

Where no other line pole is available and clearance requires it, a separate pole must be set for an anchorage. This pole is usually shorter than the line poles (22 to 25 ft. is a common length) and is usually called a "stub," see Fig. 245 (*b*). Where space allows, the stub is often set with a rake or angle to the vertical, thus relieving somewhat the stress on the base of the stub if the stub is not anchor guyed, and relieving the stress in the anchor guy if one is installed. An angle of about 20 deg. to the vertical is convenient. The setting of the stub should be reinforced by blocking of some sort to give it greater stability, especially if no anchor guy is used.

A convenient form of anchorage, where it is not necessary to provide clearance over a roadway, is an earth anchor. The *pole-to-anchor* guy is illustrated in Fig. 245 (*c*). The subject of anchors and their strength will be taken up later.

Other forms of anchorage are sometimes used, such as to trees or to buildings. The former are usually not desirable, both on

account of the possible damage to the tree and also on account of the fact that it usually is not under the control of the owner of the line and might be removed without warning. Building anchorage

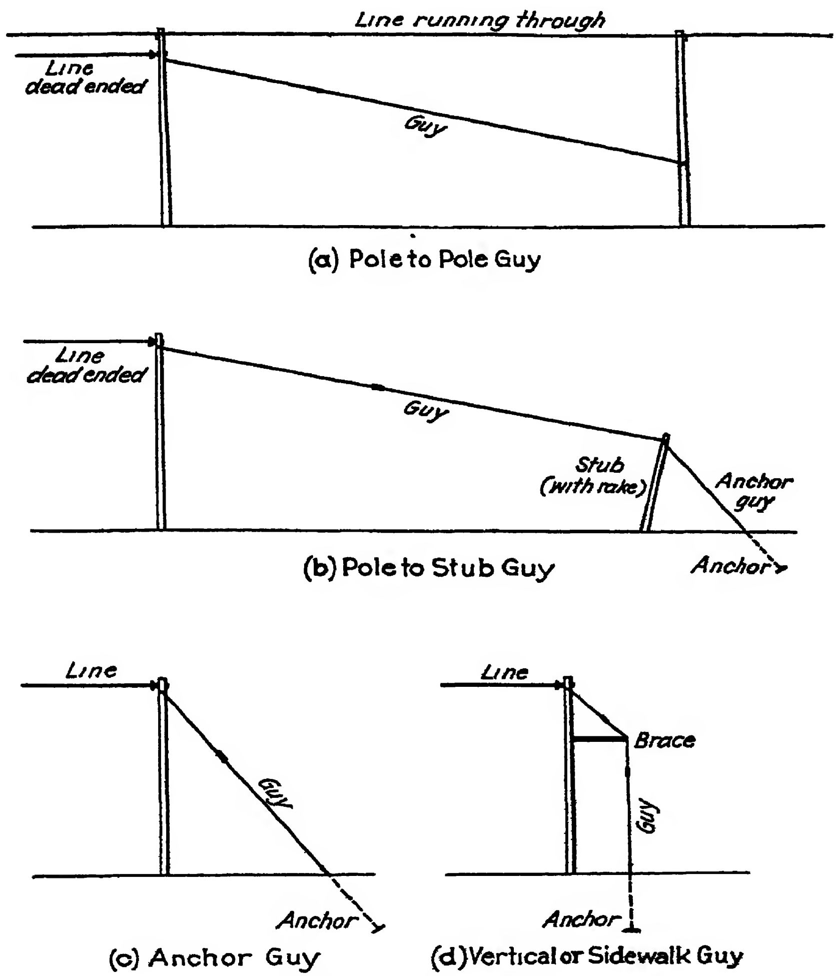


FIG 245.—Pole guys

is subject to the same objection but sometimes such construction cannot easily be avoided.

A type of guy which is used where it is necessary to provide clearance over a sidewalk or pathway, but where space is limited, is illustrated in Fig. 245 (*d*). It is sometimes called a "vertical

guy" or a "sidewalk guy." It is not particularly strong, on account of the relatively short distance from pole to anchor, and can usually be depended upon only for loads of the order of 2,000 lb. or so, even when heavy guy wire is used.

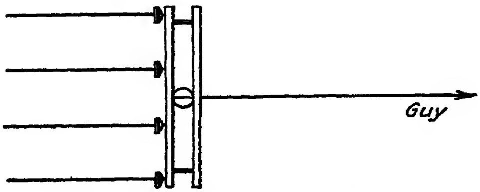
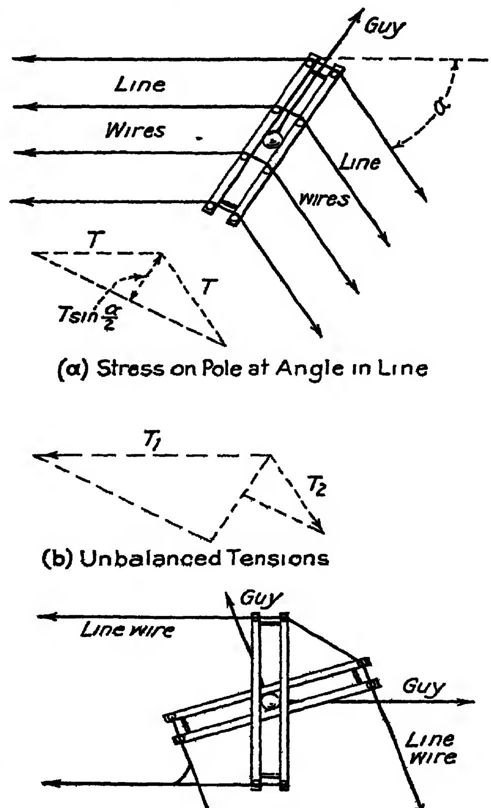


FIG. 246.—Dead end guy

Loading.—The loads impressed on guys at dead ends are due to the tensions in the wires dead ended, Fig. 246. The magnitude of these tensions depends upon the size of wire, its loading, including ice and wind, and the sag in the span. This subject was discussed in detail in Chap. XXII. The ordinary limit on which design is based is the elastic limit of the wire (about 50 to 60 per cent of the ultimate, for copper). The ordinary stress is of course usually much less than that, as the limit is reached under the worst assumed condition of loading which may be approached only occasionally.



(a) Stress on Pole at Angle in Line

(b) Unbalanced Tensions

(c) Angles Greater than 60°

FIG. 247.—Guys at angles.

At angles in the line, the loading is also due to the tension in the wires but only a component of that tension is held by the guy, the amount depending on the size of the angle in the line. Figure 247 illustrates this. If T is the assumed maximum tension in one conductor, α is the angle in the line, n the number of conductors (all alike), the component of T in the direction of the guy which bisects the angle is $T \sin \alpha/2$.

The total stress resisted by the guy is, therefore,

$$\text{for each conductor} \quad . \quad . \quad . \quad 2T \sin \frac{\alpha}{2}$$

and

$$\text{for } n \text{ conductors} \quad . \quad . \quad 2nT \sin \frac{\alpha}{2}$$

It is easy, especially if the angle is fairly large, to conceive of the loading on the span in one direction from the pole being different from that in the span in the other direction, since if the wind is directly across one span so as to have its maximum effect on that span, it will be at an angle to the other span and its effect on that will be less. This would result in different tensions in those spans as indicated in Fig. 247 (*b*) if it were not for the elasticity of the pole. The inequality of the components of T_1 and T_2 at right angles to the direction of the guy will deflect the corner pole until a balance is reached at some intermediate tension. Adjacent poles will also be somewhat deflected because the tensions in adjacent spans will have to be also adjusted. The resulting tension will be somewhere between T_1 and T_2.

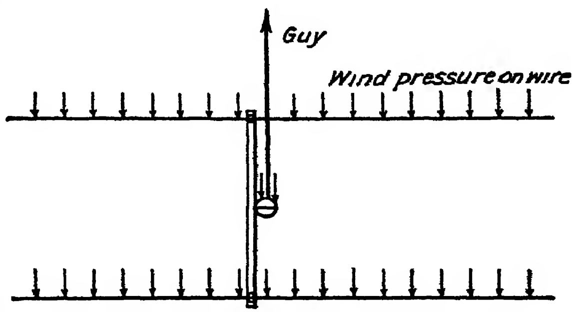


Fig. 248—Side guying for wind loading

The wind pressure on the pole itself also must be included in computing the total load sustained by the guy.

Where the angle is large, *i.e.*, more than 60 deg., the loading on a guy bisecting the angle will be greater than the dead-end loading of the line would be (except for the variation of wind loading as noted above) and it is somewhat better to install two guys as shown in Fig. 247 (*c*) if possible. In this case both guys are considered as dead-end guys.

In some cases in straight-line construction, the maximum *wind* loading on the wires will exceed the strength of the pole, in which case a guy is needed to assume the stress. The loading in this case is that of the wind pressure on the wires (with their ice covering where such is considered) in a half-span on each side of the

pole plus the wind pressure on the pole, see Fig. 248. Data on the wire loading will be found in Chap. XXII and on the pole loading in Chap. XVI. The Safety Code provides that where there are more than 10 wires with heavy- or medium-loading, spaced not over 15 in. apart, the transverse wind load may be calculated as that on two-thirds the number of wires with a minimum of 10 wires, thus making some allowance for shielding. Such guys as these are more often used at railroad crossings and similar locations where the safety factors required (by the Safety Code) are higher than for the rest of the line. They are also sometimes used on occasional poles in long lines as storm guys, not so much because the pole strength is actually insufficient for the assumed loading but rather to increase the stability of the line.

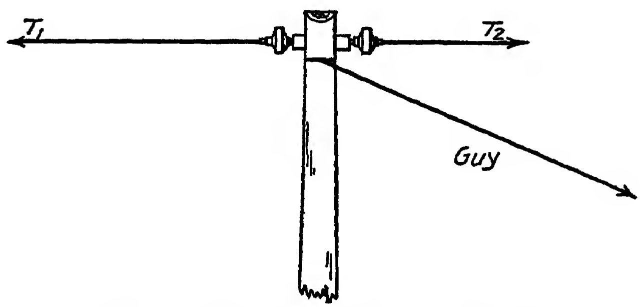


FIG. 249.—Guying for unbalanced tension

Another case of loading often encountered is at a partial dead end, *i.e.*, where a complete dead end is not held but, on account of change in wire size or difference in sag used on either side of the pole, the wire tension in one direction is less than that in the other. The balance must be taken up by guying, see Fig. 249. Such a case sometimes occurs at corners in heavy leads, where the full dead-end load is so heavy that it is impracticable to hold it all on one pole. It may be distributed over two or more poles (in each lead) by guying these adjacent poles and reducing the tension in the corner spans by increasing the sag somewhat, see Fig. 250.

Still another case of loading, when the Safety Code is followed, is where there is a section of Grade A or B construction (see Chap. XVI) in a line of lower grade of construction, such as a railroad crossing in a line otherwise Grade C or less. The Safety Code's requirement is that the structure should be able to support a

load equal to the unbalanced pull in the direction of the higher grade section (crossing) of all conductors supported. That is, sufficient strength is required to support full dead-end loading of the section. (Exception, where no span exceeds 500 ft., if the pull in the direction of the higher section exceeds 30,000 lb., the assumed loading is modified to 30,000 lb., plus one-fourth the excess above 30,000 lb., maximum 50,000 lb.)

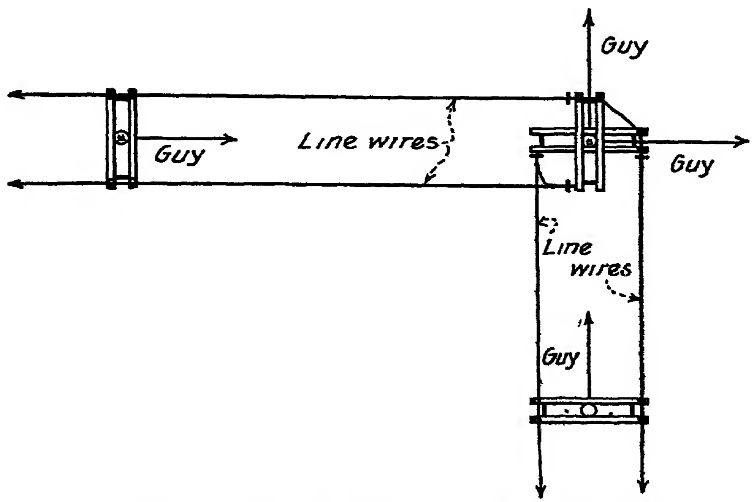


FIG. 250.—Guying distributed over several poles.

Stresses in Guys.—The loadings described above all act in horizontal planes or practically so. These horizontal stresses are counteracted by the horizontal components of the tensions in the guys.

The guy should be attached as near as practicable to the center of loading of the loads which it supports. Since the individual loads often act at different elevations, it is necessary for computation to convert them into an equivalent single load at the point of attachment of the guy. Figure 251 illustrates this. If

T_1 = loading at height h_1,
T_2 = loading at height h_2.
H = equivalent loading at point of attachment of guy, at height h.

$$H = \frac{T_1h_1 + T_2h_2}{h}. \qquad (102)$$

If wind loading on the pole is a factor, the point of application of its resultant is as shown in Fig. 180, Chap. XVI The moment of the wind pressure about the base of the pole should be added to the numerator of the above expression (in the form of $P_w h_w$).

Since the guy is rarely horizontal, the actual tension in it will be greater than H, the equivalent horizontal loading. If

γ = the angle the guy makes with the horizontal,
T_g = tension in the guy.

$$T_g = \frac{H}{\cos\gamma} \tag{103}$$

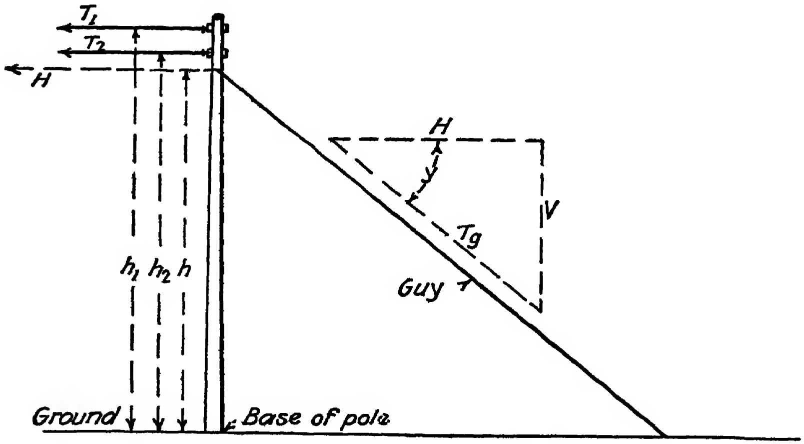


FIG. 251.—Guy loading

The vertical component of T_g, *i.e.*, V, acts as an additional vertical load on the pole itself.

Example.—Assume 4 No. 4 medium-hard copper wires dead ended on the top arm at height 33 ft. above ground, 3 No. 2 medium-hard copper wires dead ended on the second arm at height 31 ft. above ground. Guy attached 30 ft. above ground, angle of guy 45 deg.

$$T_1 = 4 \times 800 = 3{,}200 \text{ lb.}$$
$$T_2 = 3 \times 1{,}200 = 3{,}600 \text{ lb.}$$
$$H = \frac{3{,}200 \times 33 + 3{,}600 \times 31}{30} = 7{,}240 \text{ lb.}$$
$$T_g = \frac{7{,}240}{0.7071} = 10{,}240 \text{ lb.}$$

If the point of attachment of the guy is too far from the center of the load, the stress in the pole at that point may become an important consideration. The moment at that point is approximately,

$$M = T_1(h_1 - h) + T_2(h_2 - h), \tag{104}$$

the section of pole above acting as a beam (see Chap. XXX for computation of stress).

Strength of Guys.—Naturally, the strength of guys used should be at least equal to the tensions which it is computed will be imposed on them. Whether a safety factor should be used in addition will depend upon whether or not the loading assumed is considered an absolute maximum and also somewhat on the importance of the structure or its location from the standpoint of safety to the public and to the service The Safety Code specifies that the following percentages of ultimate strength shall not be exceeded.

PERCENTAGES OF ULTIMATE STRENGTH FOR DIFFERENT GRADES

	Grade A	Grade B	Grade C
For transverse strength (when installed) .	50	50	75
For longitudinal strength (at all times) in general .	100	100	
At dead ends	50	50	75

The case of the railroad crossing (Grade A or B) in a line of lower grade of construction would be an example of "longitudinal strength in general" for which this table requires only that the guy's strength at all times (even if partly deteriorated) be at least equal to the longitudinal loading assumed. This loading was discussed in a previous paragraph. Transverse guying at such locations must have a safety factor of 2 when new.

Materials for Guys.—The most commonly used material for guys is galvanized steel strand. Steel strand for this purpose comes in several different grades of strength. The ones of lower strength are softer and more easily handled in making up the guy, bending, clamping, serving up, etc. The higher strength grades are more applicable to special work where unusually heavy loads are encountered. So-called "standard strand" and "Siemens-

TABLE XLII.—CHARACTERISTICS OF STEEL USED FOR GUYS

	Ultimate strength, pounds per in.²	Elastic limit, pounds per in²
Standard	47,000	24,000
Siemens-Martin	75,000	38,000
High strength	125,000	69,000
Extra high strength	187,000	112,000

Weight	002671 lb. per cubic inch
Modulus of elasticity	29×10^6
Coefficient of linear expansion	$11\ 8 \times 10^{-6}$ per degree Centigrade
	6.62×10^{-6} per degree Fahrenheit

TABLE XLIII.—PROPERTIES OF STEEL GUY STRAND

Nominal diameter, inches	Size of strand, number B.W.G.[1]	Approximate weight, pounds per 1,000 ft.	Approximate cross-sectional area, square inches	Standard	
				Ultimate strength	Elastic limit
1/4	14	121	0 0379	1,900	1,000
9/32	13	157	0 0496	2,500	1,250
5/16	12	205	0 0653	3,200	1,600
3/8	11	296	0 0792	4,250	2,100
7/16	9	399	0 1205	5,200	2,600
1/2	8	517	0 1495	7,400	3,700
9/16	.	671	0 1823	9,600	4,800
5/8		813	0 2330	11,600	6,000
3/4		1,200	0 3360	16,700	8,500

Nominal diameter, inches	Siemens-Martin		High strength		Elastic strength	
	Ultimate strength	Elastic limit	Ultimate strength	Elastic limit	Ultimate strength	Elastic limit
1/4	3,060	1,500	5,100	2,800	7,600	4,600
9/32	4,380	2,200	7,300	4,000	10,900	6,500
5/16	4,860	2,400	8,100	4,500	12,100	7,300
3/8	6,800	3,400	11,500	6,300	17,250	10,350
7/16	9,000	4,500	15,000	8,250	22,500	13,500
1/2	11,000	5,500	18,000	9,900	27,000	16,200
9/16	19,000	9,500	25,000	13,750	42,500	25,500

[1] B W G refers to Birmingham Wire Gauge.

Martin" are the ones most used for guying distribution lines. The characteristics of these grades of wire are given below. Table XLIII gives strength for the usual commercial sizes.

Ordinarily the wire up to ½ in. is made with 7 strands, the larger sizes (⅝ in. and ¾ in.) being usually 19 strand, giving more flexibility. Larger sizes than those shown are also obtainable but are not often used for ordinary guying.

Another grade of wire is sometimes used, being specified by its strength rather than diameter. (This is common practice for messenger and guys for telephone lines.) Its characteristics are as follows:

Strength, Pounds	Stranding (Number × Diameter in Inches)
6,000	7 × 0 109 (No 12 B W.G)
10,000	7 × 0 120 (No 11 B W G)
13,000	7 × 0 148 (No. 9 B.W G)
16,000	7 × 0 144 (No. 9 N B S [1])
21,500	7 × 0 203 (No. 6 B W G)
30,000	19 × 0 109 (No. 12 B.W.G.)

[1] N B S New British Standard

In some localities, notably where there is a great deal of coal smoke in the air and where salt spray or salt fog is prevalent, galvanizing has a comparatively short life. While under favorable conditions good hot-dip galvanizing will have a life of 15 years or more, under such conditions as indicated above, the effective life will sometimes be no more than 4 or 5 years, sometimes even less. After the galvanizing protection has been removed, the steel very quickly becomes corroded and is soon of little value as a guy. In such locations the cost of maintenance with galvanized steel often warrants the use of some material of longer life, even at a considerable increase in the cost of the material itself. Copper-covered steel is one material which is available for this purpose. Its characteristics were discussed to some extent in Chap. XXII. The grade used for guying has a thinner coating of copper than that ordinarily used as a conductor. The copper covering is a very effective resistant to most ordinary forms of corrosion. Two grades of strength are available called "standard tensile" and "extra high tensile." Table XLIV gives he characteristics of commercial sizes of this wire.

TABLE XLIV.—PROPERTIES OF COPPER-COVERED STEEL STRAND

Nominal diameter, inch	Actual diameter, inch	Number of wires and size (A.W.G.)	Breaking load,[1] pounds	Cross-section, square inch	Allowable tension, pounds
Standard Tensile, Hard Drawn					
3/4	0.772	19 No. *	31,200	0.354	15,600
23/32	0.720	19 No. 7	27,600	0.311	13,800
11/16	0.681	19 No. *	25,100	0.275	12,550
5/8	0.640	19 No. 8	22,800	0.246	11,400
5/8	0.612	7 No. 4	18,550	0.229	9,280
9/16	0.570	19 No. 9	18,430	0.195	9,220
9/16	0.546	7 No. 5	15,400	0.182	7,700
1/2	0.486	7 No. 6	12,600	0.144	6,300
7/16	0.432	7 No. 7	10,160	0.114	5,080
3/8	0.384	7 No. 8	8,400	0.0910	4,200
11/32	0.342	7 No. 9	6,790	0.0719	3,400
5/16	0.306	7 No. 10	5,600	0.0571	2,800
9/32	0.273	7 No. 11	4,550	0.0452	2,280
1/4	0.243	7 No. 12	3,640	0.0360	1,820
3/16	0.192	7 No. 14	2,310	0.0226	1,160
Extra High-tensile Grade					
3/4	0.772	19 No. *	44,600	0.354	22,300
23/32	0.720	19 No. 7	39,160	0.311	19,580
11/16	0.681	19 No. *	34,800	0.275	17,400
5/8	0.640	19 No. 8	31,120	0.246	15,560
5/8	0.612	7 No. 4	28,980	0.229	14,490
9/16	0.546	7 No. 5	22,930	0.182	11,465
1/2	0.486	7 No. 6	18,200	0.144	9,100
7/16	0.432	7 No. 7	14,420	0.114	7,210
3/8	0.384	7 No. 8	11,460	0.0910	5,730

[1] Breaking load of strand is taken as 90 per cent of the sum of the breaking loads of the individual wires of the quality used in strand manufacture

* Special gauge wire (not an A.W.G. size)

(Compiled by Copperweld Steel Company.)

Copper-alloy wire is also suitable for this purpose. Several types of bronze and brass wires are available. Two examples of commercial wires have the following characteristics:

Grade name	Tensile strength, pounds per in.²	Elastic limit, percentage	Weight, pounds per in.³	Electrical resistance compared with copper, percentage
Calsun bronze .	119,000 to 121,000	60	0 3212	15
Red brass	110,000 to 115,000	60	0.313	25

Modulus of elasticity and temperature coefficient of expansion about the same as for copper

Attachment of Guys.—*Arm guys* are generally attached to the arm by means of an eyebolt, the wire being protected by a thimble, bent back on itself, and clamped or served, see Fig. 252 (*a*).

Pole guys are usually given two or more turns about the pole and clamped, see Fig. 252 (*b*). It is ordinarily good practice, especially with comparatively soft wood such as cedar and where the guy stress is fairly heavy, to protect the pole by plates or shims under the guy. *Guy hooks* are used as shown in Fig. 252 (*b*) to prevent the guy from slipping along the pole. On Fig. 253 are illustrated a typical shim, plate, and guy hook. In some places there are regulations against passing the guy around the pole, in which case an eyebolt through the pole is the method used. Where the angle of the guy is steep the downward component on the bolt is likely to crush the wood of the pole unless special means are taken to reinforce that point.

Attachment to buildings may be made with a wall strap as shown in Fig. 252 (*c*). Where the guy tension is heavy, especial attention should be paid to getting a secure anchorage to the wall. Sometimes an eyebolt passed through the wall and secured on the other side can be used for this purpose.

Where a guy must be attached to a tree, the tree should be protected from damage as shown in Fig. 252 (*d*).

Wherever a guy passes through an eyebolt or the eye of an anchor rod it should be protected by a metal thimble. Otherwise the strands will spread under the tension and will be unequally stressed, the strength of the guy being thereby reduced. Care should be taken not to get the thimble of such a large cross-section compared with the size of the guy wire that it does not

have the desired retaining effect. Anchor-rods and eyebolts are sometimes forged into thimble shape for this purpose but

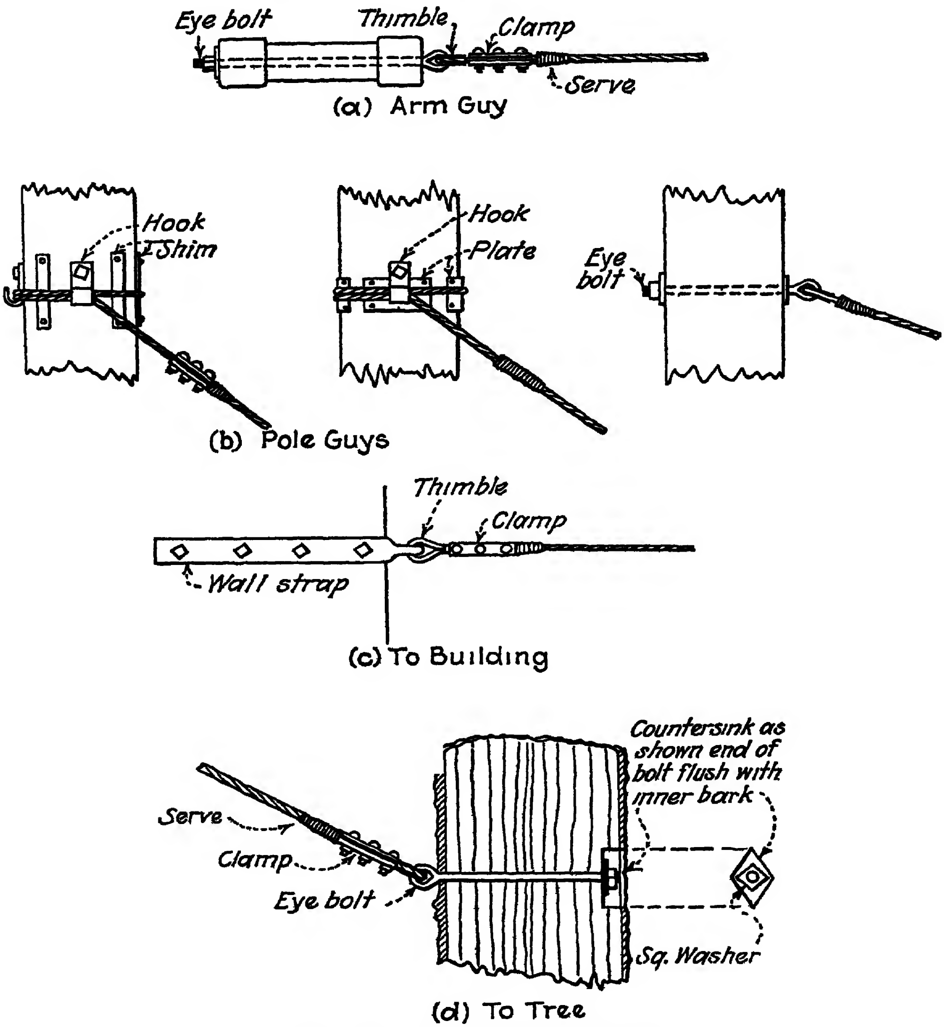


FIG 252.—Attachment of guys.

unless the shape is such as to prevent the strands from spreading, the special eyes are not effective.

Two methods are commonly used for securing the end of the guy wire after forming a loop through an eye, an insulator, or around a pole, *i.e.*, serving and clamping. In *serving*, the strands

of the wire are separated and wrapped separately around the "standing" part of the guy, as indicated in Fig. 254 (*a*).

Two general types of *clamps* are in common use. One consists of two plates fastened together by bolts, with the guy wire

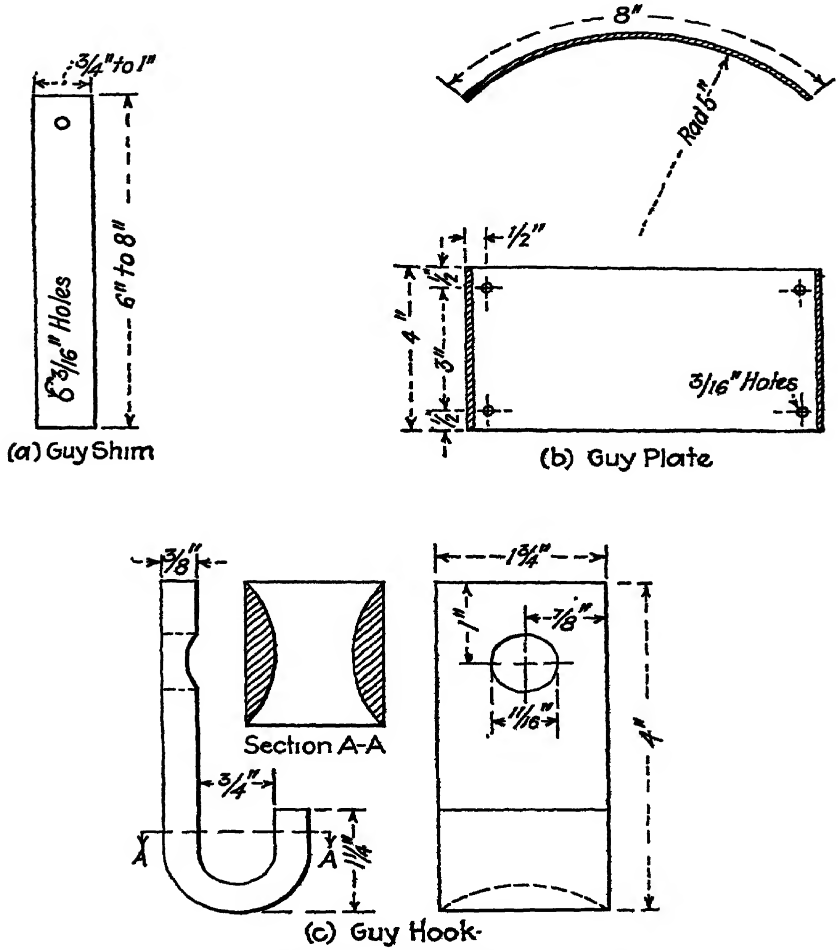


FIG. 253.—Guy shim, plate, and hook.

held between them. The ordinary three-bolt clamp, Fig. 254 (*b*), is an example of this type. These are sometimes made with the plates having grooved or corrugated surfaces or waved surfaces, etc., with the idea that they will grip the wire better or may have a snubbing action. Such shapes, however, may defeat

their own purpose The holding power of the clamp depends largely upon the friction between it and the wire and a plain-faced clamp will usually have more bearing surface on the wire, and hence more friction, than one with corrugations. Wave-shaped plates may be quite effective with some sizes of guy wire but the larger, stiffer wire cannot be readily bent to conform with short waves, especially when the clamp is applied with the guy under tension, which is quite often the case.

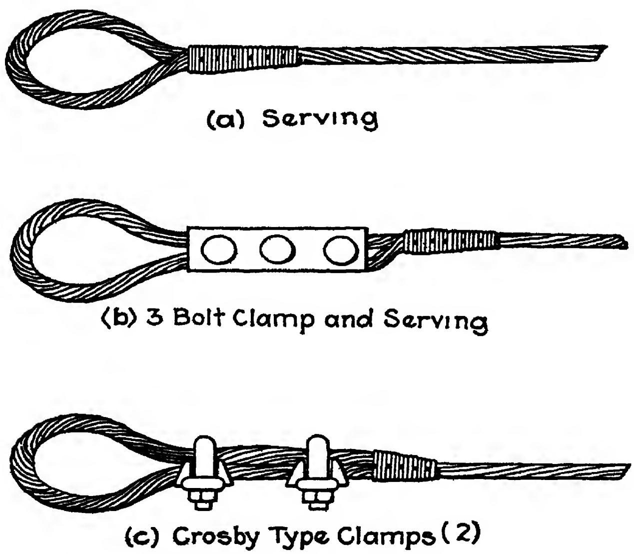


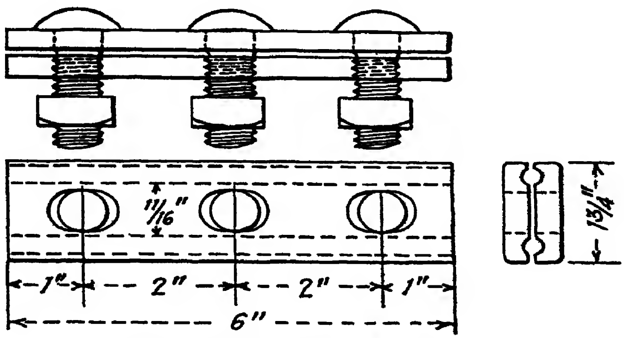
Fig. 254.—Serving and clamping

The other type of clamp is quite commonly designated as a "Crosby clip," also as a "guy clip," and as a "wire rope clamp." It consists essentially of a short plate (usually with spiral grooves to fit the strand), and a U bolt, see Fig. 254 (*c*). These are very effective clamps but are somewhat more difficult to apply and tighten than the type mentioned above, especially in the smaller sizes. In assembling them on the wire, care should be taken to have the plate against the *standing* part of the guy and the U bolt against the end portion, see Fig. 254. The U bolt bites into the wire somewhat or at least distorts the strands and if placed against the *standing* parts on which the main tension is held, it is likely to weaken the wire.

Figure 255 shows the National Electric Light Association suggested standard for three-bolt clamp and guy clip.

Two or more clamps of either type may be used if the tension in the wire warrants it. Usually the end of the wire beyond the clamp is served up somewhat to fasten it down and also to add to the strength

Other types of clamps are made, such as the various forms of boltless clamp. These latter have never found very general use probably very largely on account of the fact that they usually depend upon the guy remaining under tension in order for them



(a) 3 Bolt Guy Clamp

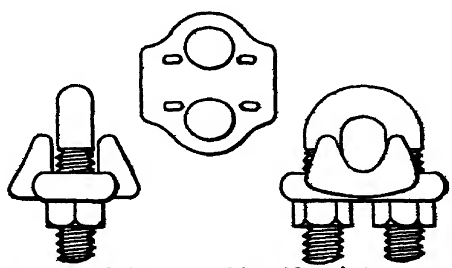

(b) Guy Clip (Crosby)

FIG. 255 —Guy clamps.

to remain in place. The guy is quite likely to slack off at times as the pole moves in the wind.

Some tests made on various types of guy clamps showed that it was unusual for a single clamp to be able to hold the connection without slipping under heavy stress. The same is true of a serving In most cases however, after the connection had slipped up against the thimble, it held so as to break the wire. One clamp and an additional short serving was found of practically as great strength as the wire. Standard strand was used in

the test. For higher strength strand the strength of the connection should be increased accordingly.

Guy Insulators.—It is usually a good policy to insert at least one insulator in a guy to prevent the part of the guy attached to the pole from being at ground potential under normal conditions or if broken. This is a protection for men working on line circuits on the pole, for the public, and also sometimes prevents accidental interruptions to circuits. For adequate protection, the insulator should be far enough out from the pole to be beyond easy reach. A minimum distance of 6 ft. is advisable where practicable. The insulator also should be out of reach of a person on the ground, *i.e.*, 8 or 10 ft. aboveground. It is preferable also that it be placed where it will not swing within 8 ft. of

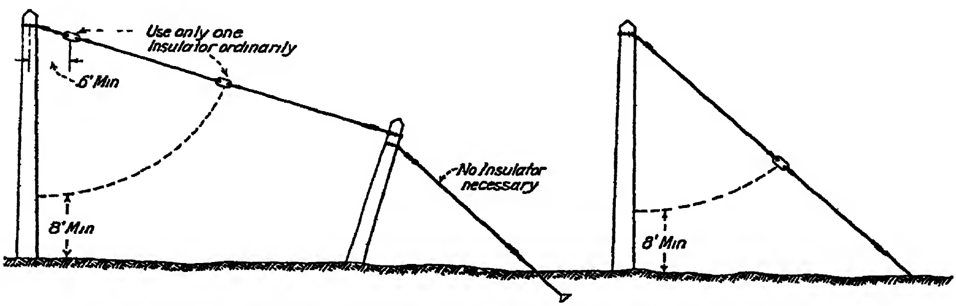


Fig 256.—Location of guy insulators.

the ground in case the guy breaks at or near its lower end, see Fig. 256, although it should, at the same time, be low enough to be below any point where it might come in contact with a live circuit. The reason for this is, obviously, to protect the public in the case when the upper end of the guy is most likely to be in contact with line circuits. In some cases, two insulators should be used for adequate protection, such as where the guy crosses over or under other supply conductors in such a way that, if either the conductors or the guy should break, contacts would be likely. An insulator each side of the exposed section is advisable. In general, care should be used to have enough insulators and so arranged that the public, the circuits, and workmen on the pole will be as effectively protected as possible under all conditions which may be reasonably expected.

Protectors.—Where a guy comes within 8 ft. of the ground (an anchor guy for example) the lower portion should be made more visible as a protection against being run into by persons

or vehicles. This is sometimes accomplished by slipping a piece of pipe over the wire. Special protectors are available for this purpose which are convenient to install after the guy is in place Figure 257 shows the application of these protectors and two commercial types.

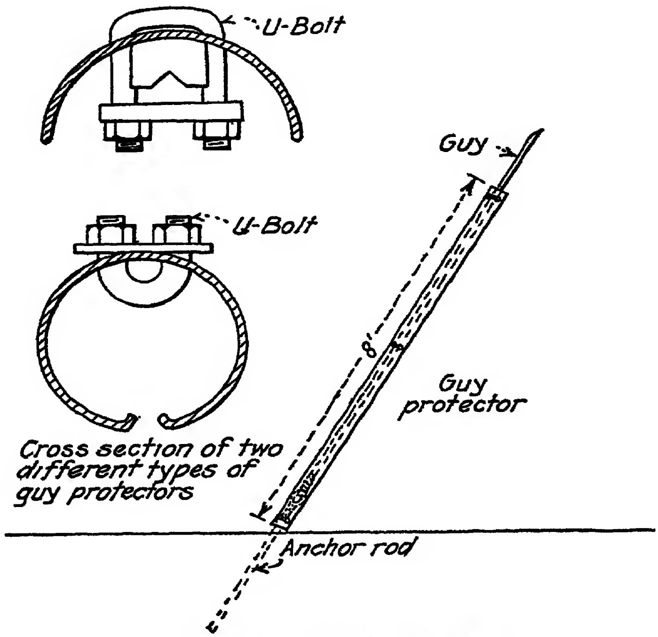


FIG. 257.—Guy protectors

Clearances.—Clearances for guys were included in the tables given in Chap. XXIII.

Anchors.—The proper selection of a ground anchor for an anchor guy is one of the most important features of the guying problem. It is also one about which there is comparatively little accurate information available. Soil conditions are extremely variable, even in the same general locality, and conditions change somewhat with the seasons. It is obvious that the anchor should have at least as much holding power as the strength of the guy with which it is used. Holding power in this case should mean the load at which the anchor moves appreciably, not its ultimate strength, for if the anchor *gives up* any considerable amount, the guy slacks off and damage may be done. With the present limited knowledge of the action of

anchors under various conditions, a good safety factor is advisable.

The theory of the holding power of an anchor is not well established. It is sometimes assumed that the holding power of the anchor is equal to the weight of a cone of earth whose apex is the anchor and whose sides are at the slope of the natural angle of repose of the soil, see Fig. 258. This would probably be approximately true if the area of the anchor were big enough. However, it will be found in testing anchors, that the surrounding earth is usually not disturbed until the anchor has been pulled out to within a comparatively short distance of the surface. The cone action then takes place. The explanation would seem

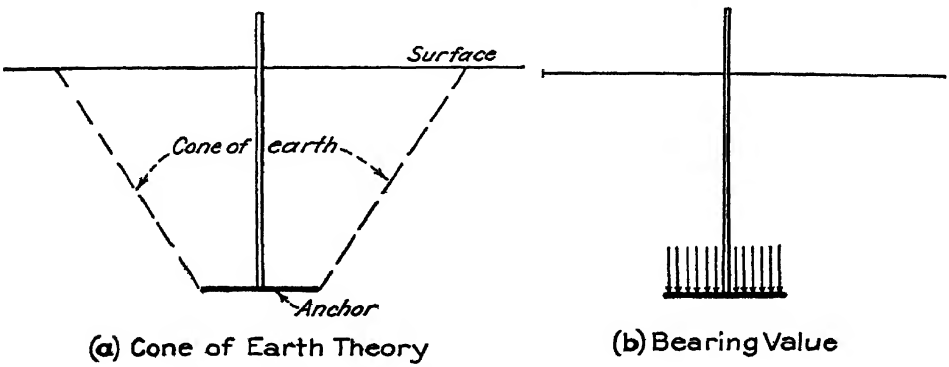


Fig. 258.—Holding power of anchor

to be, obviously, that the soil has a certain bearing value per square inch of anchor surface. When this is exceeded, the anchor will move through the earth. If the weight of the cone of earth above it is less than the bearing strength of the soil on the anchor, the cone theory will apply. If the weight of the cone is greater however, the holding power of the anchor will depend largely on its area multiplied by the unit-bearing value of the soil (Fig. 258 (*b*)). This is the more usual case. Other factors also enter the problem, such as the shape of the anchor and the condition of the soil whether wet or dry, packed or loose, disturbed or undisturbed, etc. No definite values can be given for soil bearing for anchors. Some tests observed have seemed to indicate values of about 75 lb. per square inch for some soils, such as loose dry sand, whereas finer, hard-packed sand with more moisture has shown values above 300 lb. per square inch. Clay does not seem to have as good holding power as sand when

it is wet (and that is the condition which must be assumed for certain seasons of the year at least), the values observed being not much greater than 75 to 100 lb. per square inch The following values are given in "Foundations of Buildings and Bridges" by Jacoby and Davis, for allowable bearing values of various soils as averaged from the building codes of 40 large cities. They are *allowable* values and are probably not less than one-half of what actual values will be found by test. Also the bearing for foundations may be somewhat different than that for anchors. The figures are given for comparison however.

TABLE XLV —ALLOWABLE BEARING VALUES FOR FOUNDATIONS—AVERAGE OF BUILDING CODES OF 40 CITIES

	Tons per Square Foot
Quicksand and alluvial soil	0 5
Soft clay	1
Moderately dry clay, fine sand	2
Firm and dry loam or clay	3
Compact, coarse sand or stiff gravel	4
Coarse gravel	6
Gravel and sand, well cemented	8
Good hardpan or hard shale	10
Very hard, native bedrock	20

It is not intended that these values be assumed as even typical. Independent tests on anchors under local conditions are to be recommended as a basis for making a proper choice.

Types of Anchors.—A type of anchor commonly used, especially where the load is heavy or the soil soft or where more than one guy is to be attached, is the *dead-man.* It consists of a sound log, a block of concrete, or a steel member of some sort, that will give the desired bearing area, with the anchor rods attached to it. Figure 259 (*a*) illustrates a *dead-man* and the proper method of installation.

For anchoring each guy individually (and this is a good general practice) so-called "patent anchors" of various kinds have come into quite general use. Although there are any number of different kinds on the market they fall into four general classes as follows:

1. *Expanding Anchors.*—These are designed to be set in a small hole (6 or 8 in. is common) and be expanded, by pounding the anchor or twisting the rod, to a much larger area, Fig. 259 (*b*). Their value lies in being able to thus get a definitely determined

bearing area of reasonably good size, a large part of which is in undisturbed earth. The tamping of the earth in the hole does not play as large a part as in some types of anchors, although it

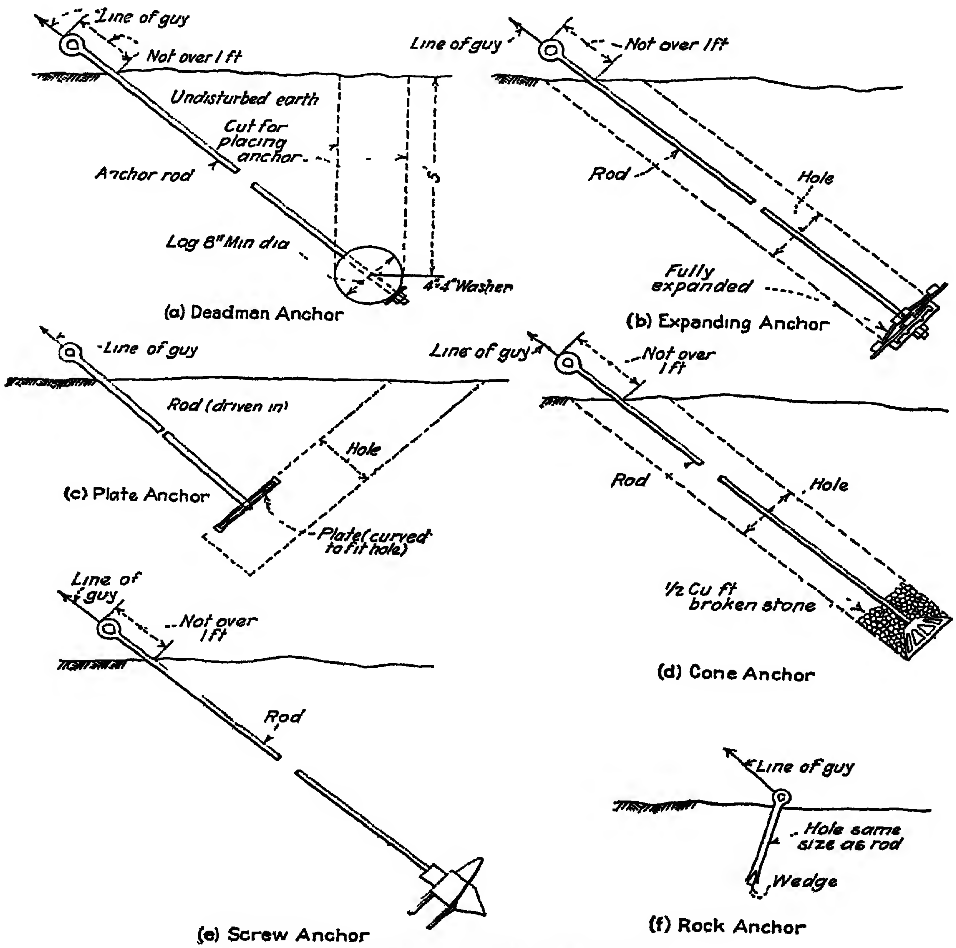


FIG. 259.—Types of anchors.

does add to the holding power if the soil is well packed in the hole.

2. *Plate Anchor*, Fig. 259 (*c*).—This type is similar in principle to a dead-man. The hole is dug at approximately right angles to the line of the guy, the anchor rod driven in at the desired point, and the plate placed on the end of the rod. It has the advantage of having practically all of its bearing on undisturbed

earth but is somewhat harder to install than some of the other types.

3. *Cone Anchors*, Fig. 259 (*d*).—The anchor is a casting in the form of a cone. It is installed in a hole of the same diameter as the anchor. About ½ cu. ft. of broken stone is tamped in on top of the cone. The holding power depends on the action of the cone forcing some of the stone out into the surrounding earth, increasing the effective area of the anchor both in projected area at right angles to the direction of the guy and also in its wedge effect. For best results the stone should not be too fine (3 in. size has been found satisfactory). This type of anchor is suitable for many locations but is not so well adapted to very hard soils, where the stone has not the chance to spread, or to very loose or wet soils, where the stone may spread too easily. In such locations if the stress is heavy, troubles may be found with creepage even where the initial installation appears solid. The 8 in. size is the most commonly used but larger sizes are made.

4. *Screw Anchor*, Fig. 259 (*e*).—This type is screwed down into the soil without digging a hole. Sometimes a special key is used for the purpose which fits over the rod and engages the head; sometimes the rod is made large enough to withstand the torsional stress of installing the anchor. It has the advantage of eliminating the digging of a hole, which may be especially desirable in some locations, such as in a customer's lawns. It also may be installed under water or in marshes, where a hole cannot be dug. In hard soils, however, it is often rather difficult to install unless a small "leader" hole is dug. Its area is necessarily somewhat limited by the size which can be screwed into the earth. The most commonly used are 6- and 8-in. sizes.

Anchor rods for attaching the guy wire to the anchor are made in various sizes from ½ to 1 in., ⅝ in. being probably the most used. The size of rod should be gauged somewhat by the strength of the guy with which it is used or which may later be attached to it. As a rule the length should be not less than 6 ft. in order that the anchor may be buried deep enough to develop its strength. The rod should be galvanized.

Anchorages in rock are made as shown in Fig. 259 (*f*).

Push Braces and A Frames.—Although not classed as guys, wooden structures, such as poles with wooden push braces or A frames, are sometimes used instead of guyed poles where guys are inconvenient or impossible to install. Figure 260 shows typi-

cal examples of such structures. They are sometimes useful on long curves where every pole or every other pole would otherwise have to be guyed, especially where the guys must cross the road

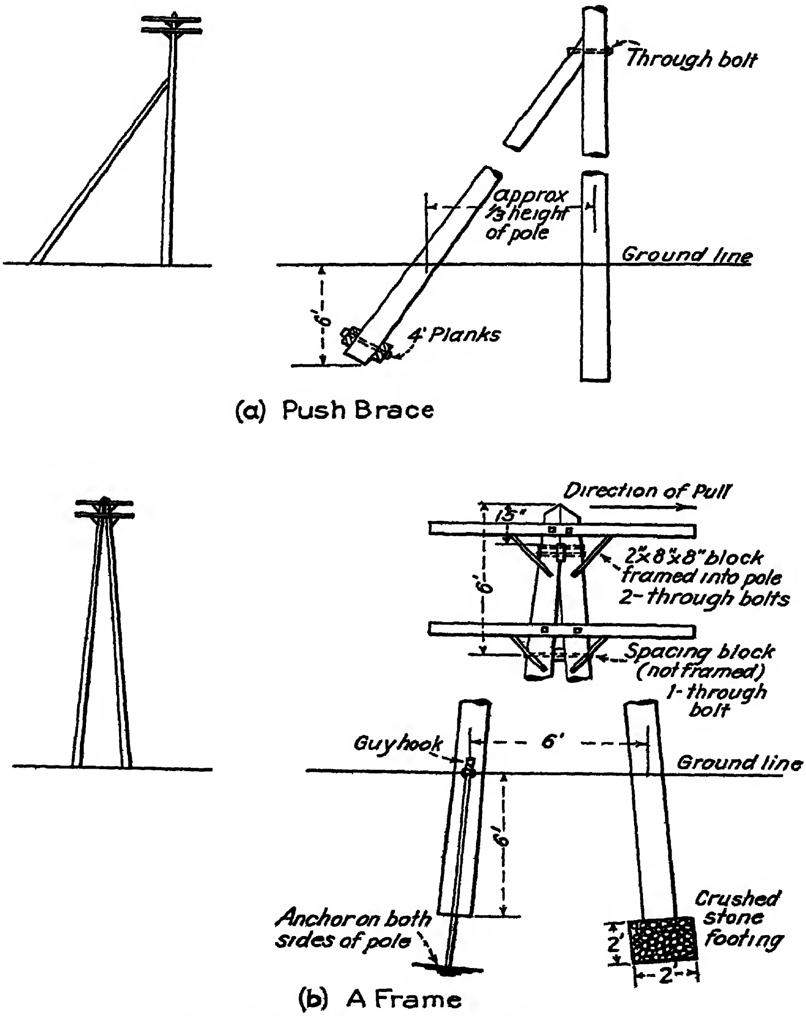


Fig. 260.—Push brace and A Frame.

and stubs on the other side would be necessary. One difficulty in their use in some places is the necessity for getting locations for two poles instead of one. The A frame, although somewhat more sightly, is limited in strength and if properly constructed will probably cost more than an equivalent guy.

CHAPTER XXV

TRANSFORMER INSTALLATIONS

Transformers constitute the most usual type of heavy load, except wire loading, which distribution line poles are called upon to support. There are certain features of the mechanical design of transformer installations which are worthy of careful attention, especially for the heavier sizes. These will be pointed out briefly in this chapter.

The transformer imposes a vertical loading on the pole which acts as a column to support it. The pole should of course be of sufficient cross-section to withstand this loading, taking into consideration the fact that it is a more or less slender column. The strength of poles in this respect was discussed somewhat in Chap. XVI and a column formula given. The slenderness effect in the column is aggravated in the case of a transformer hung on cross-arms by the fact that the load is excentric to the axis of the pole. Allowance should be made for this in computing the unit stress in the pole, an ample safety factor being a simple method of taking account of it. As a rule there is little difficulty in obtaining sufficient pole strength in this regard with the sizes of poles ordinarily used. The following rule has been found to be quite satisfactory on one system

Transformer Size	Minimum Pole Size
1½ to 15 kv-a., single-phase	Class C
25 to 50 kv-a., single-phase	Class B
75 to 100 kv-a., single-phase	Class A
5 to 25 kv-a., three-phase	Class B
37½ to 100 kv-a., three-phase	Class A

The weight of the present designs of distribution transformers is approximately as given in Table XLVI.

Cross-arm Mounting.—The smaller sizes of transformers—up to 50 kv-a. at least—are commonly mounted on the side of the pole on cross-arms or their equivalent. Figure 261 is a typical example of a simple mounting for a light transformer. In looking

TABLE XLVI.—APPROXIMATE WEIGHTS OF DISTRIBUTION TRANSFORMERS[1] (WITH OIL)

Kilovolt-amperes	Single-phase				Three-phase	
	60 cycle		25 cycle		60 cycle	
	Up to 4,800 volts	6,600 volts	Up to 4,800 volts	6,600 volts	Up to 4,800 volts	6,600 volts
1½	180	250	265	235		
3	285	275	395	395		
5	295	390	470	405	440	
7½	400	410	515	445	535	
10	415	430	675	605	765	790
15	540	590	785	720	850	965
25	815	875	1,195	1,230	1,390	1,430
37½	1,060	1,010	2,095	1,480	1,520	1,490
50	1,250	1,330	2,250	1,660	2,160	1,860
75	1,575	1,630	2,640	2,570	2,510	2,900
100	1,760	1,790	3,550	2,870	2,530	3,450
150	3,030	3,480	4,540	4,190	3,610	4,450
200	3,320	3,700	5,930	4,670	4,160	5,000

[1] These are the weights listed by one manufacturer only and are given as an example. The weights of transformers made by other manufacturers will be somewhat different, but the above are typical

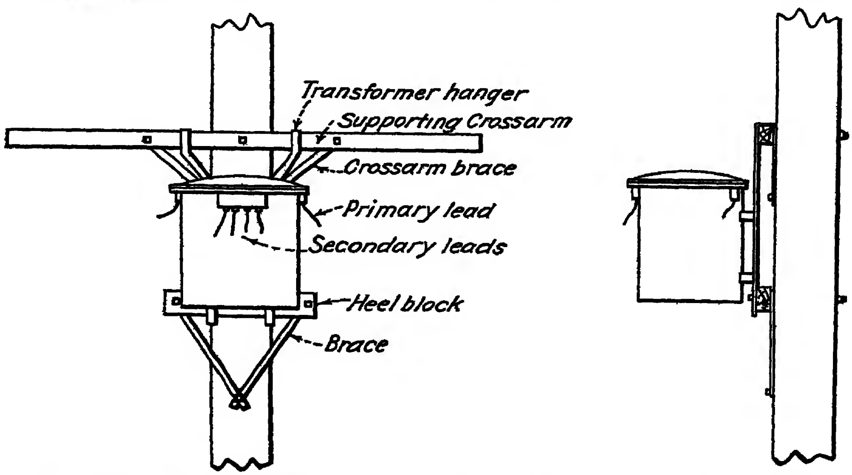


FIG. 261.—Typical installation for light transformer—single-phase.

over the details of the construction, the following points may be noted as requiring investigation of the strength of the parts,

especially when the weight of the transformer is considerable. It must be remembered that the full weight of the transformer is transferred to the pole through the various mechanical connections.

1. Bearing of transformer hanger on the cross-arm.—The width of the hanger should be such that its bearing surface on the arm will be large enough to prevent crushing of the wood, taking account of the fact that the load is probably not uniformly applied over the width of the arm. The ultimate bearing value of fir under such loading (across the grain) is given as 800 lb. per square inch, of yellow pine 1,000 lb. per square inch.

2. Strength of the cross-arm acting as a beam, loaded at the points of bearing of the transformer hangers and supported at the through bolt through the pole and at the points of attachment of the braces.—Where flat cross-arm braces are used, it is somewhat doubtful whether they will take their full share of the load on account of their flexibility. In such cases it is probably safer to assume that the cross arm through bolt takes at least 75 per cent of the total load.

3. Bearing value of arm on through bolt.—The arm may be assumed to have uniform bearing on the bolt, *i.e.*, W/dt, where

W = load

d = diameter of bolt.

t = thickness of cross-arm.

Bearing value of wood as given above in (1).

4. Bearing value of bolt on pole.—This was discussed in Chap. XVII under cross-arm strength and need not be repeated here.

5. Where heavier braces, such as angle irons, are used, which will assume their full share of the load, the bearing values of brace bolts on cross-arm, and through bolt or lag (where brace is attached to pole) on pole must be considered.

For heavy transformers, some means must usually be adopted for reinforcing the connection to the pole (some typical examples, Fig. 262). The plain double arm is not to be recommended as it will be little if any stronger than a single arm under such loading (see Chap. XVII).

From the standpoint of strength of poles and stability of construction, the lower a transformer can be hung on a pole the better. On the other hand, the higher it is, the less likelihood of its being tampered with by unauthorized persons, also, in

general, the neater and more compact the installation can be made. A high installation is particularly necessary where joint construction with communication lines is practiced or where such

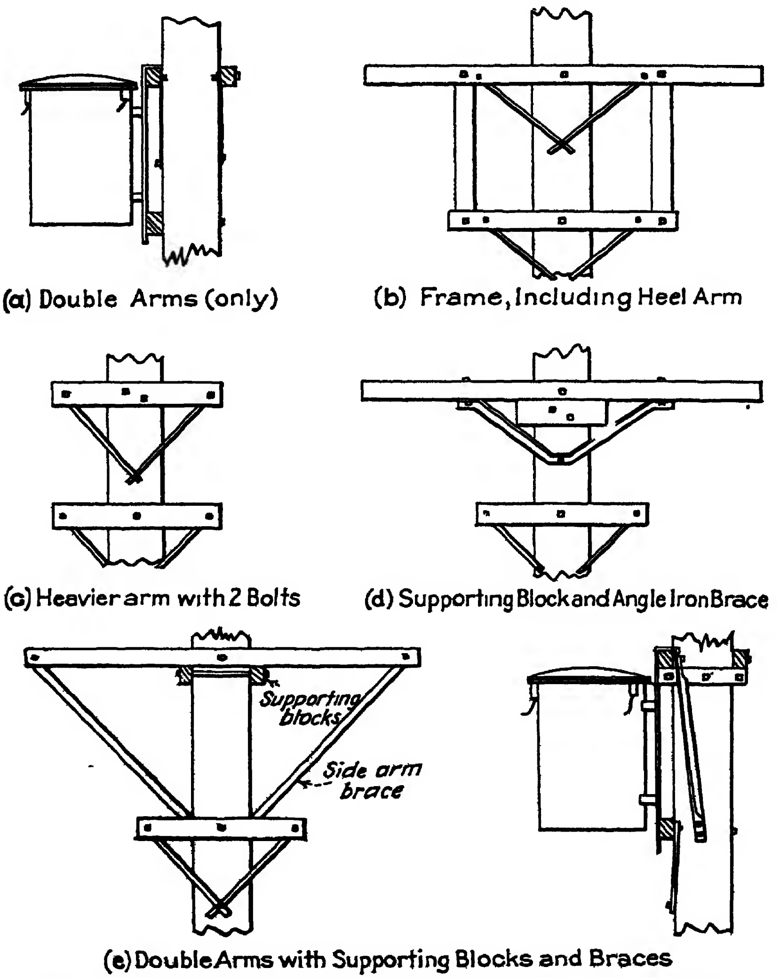


FIG. 262.—Reinforcement of support for heavy transformers

lines parallel or cross the location, even though not attached to the pole. Some companies carry the transformer on the top cross-arm of the pole but this is a rather inconvenient location for installation or maintenance if the transformer is a large one. Figure 263 (*a*) shows a typical installation on the top arm, Fig. 263 (*b*) one on a lower arm. The former is convenient for use on

farm lines where only one primary circuit will ever be carried and transformers are small.

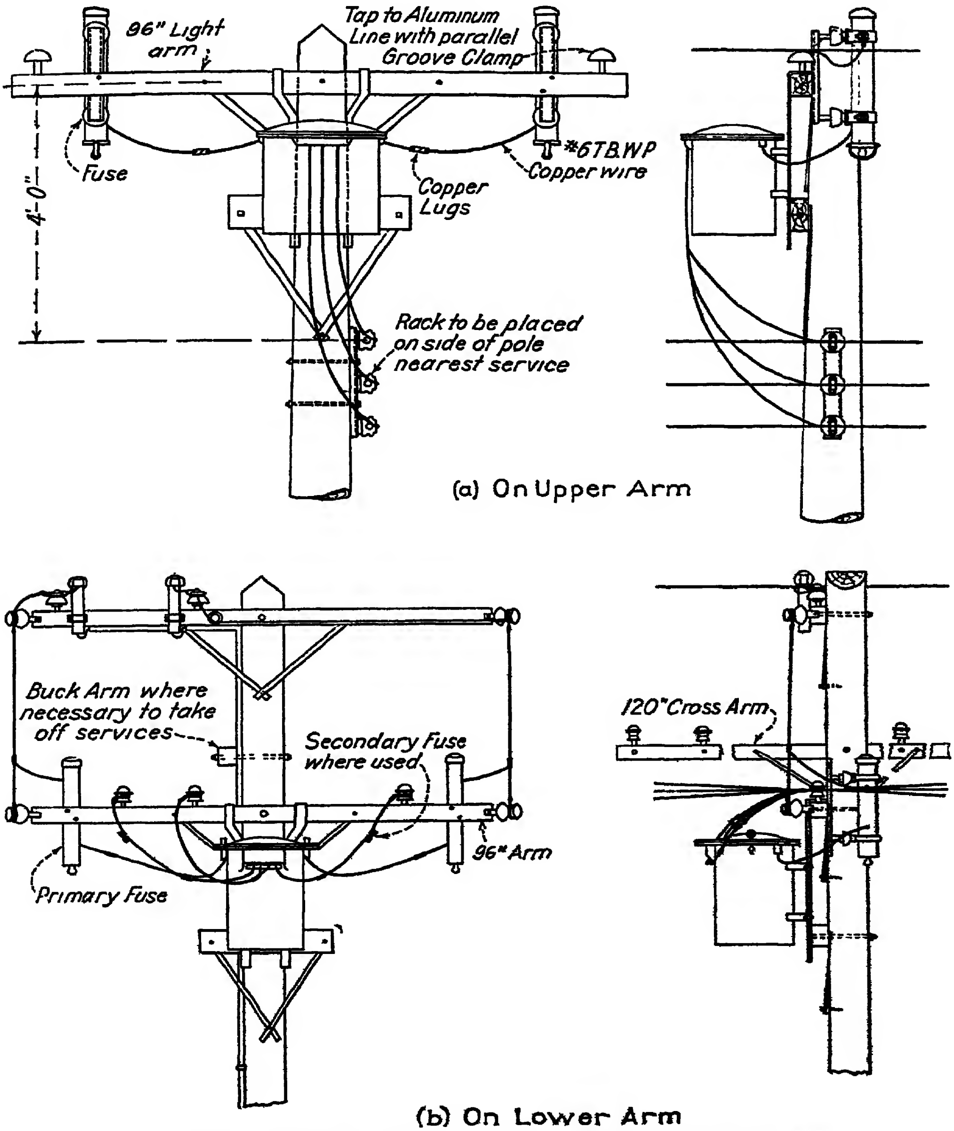


FIG. 263.—Typical transformer installations, single-phase.

Figure 264 shows a typical installation of a three-phase transformer.

Figure 265 shows a three-phase installation using three single-phase transformers.

Figure 266 shows a single-phase installation on side-arm poles.

Platforms.—Transformers which are too heavy to be safely supported on cross-arm construction may be installed on platforms.

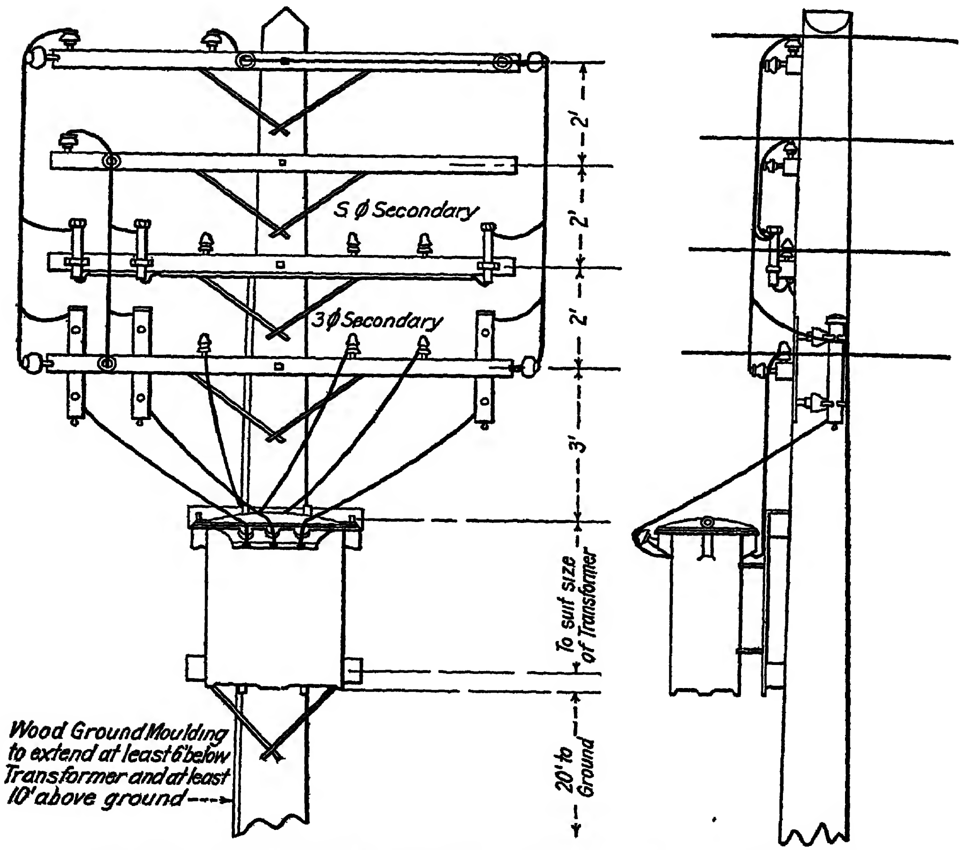


FIG. 264—Typical transformer installation—three-phase transformer.

A platform is also a convenient support for use where more than one transformer is needed, such as three-phase installations with single-phase transformers (except with small sizes).

The ordinary platform construction consists essentially of two (or more) poles supporting a pair of beams upon which a flooring of some sort is laid to carry the transformers, see Fig 268. The points whose strength must be specially considered are:

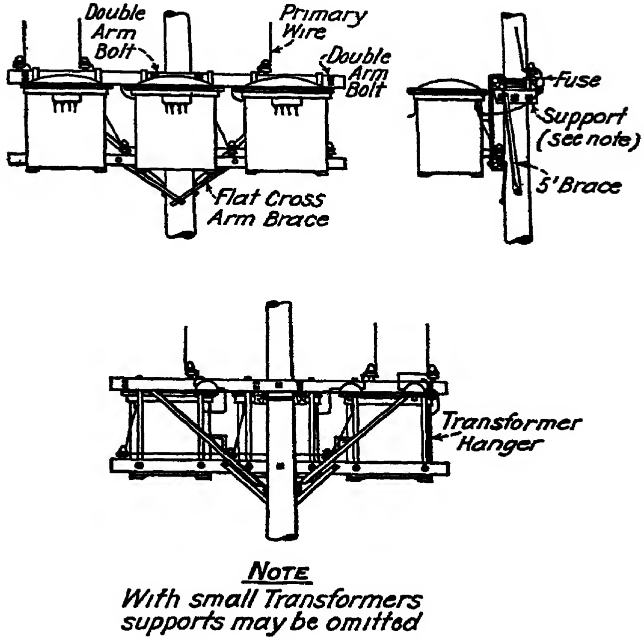


FIG. 265 —Typical transformer installation—three-phase with single-phase transformers.

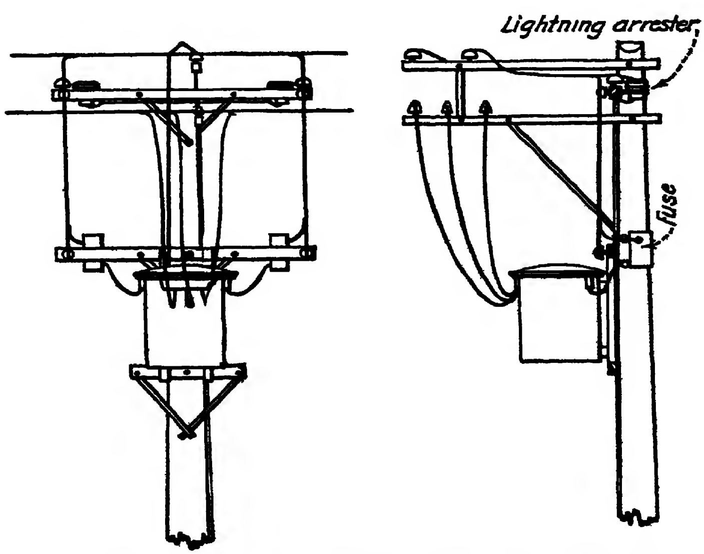


FIG. 266 —Typical transformer installation—side arm.

1 *The Beams.*—These are made either of wood timbers, 2 by 12 in., either singly or double as required, or 4 by 12 in. are convenient sizes, or steel structural shapes. A steel channel is probably the most suitable shape. The size of beam required of either material may be determined by the usual beam formulæ (see Chap. XXX).

2. *The Points of Attachment of Beams to Pole.*—The full load assumed by the support (one-half the total weight carried if only two poles are used) is transmitted from the beams to the pole through the bolts used for the connection. Sufficient bolts must be used so that their bearing stress on the wood of the pole (and the beams) does not exceed the allowable bearing strength of the wood (5,500 lb. per square inch ultimate end bearing on cedar). Figure 267 indicates approximately how this stress is distributed over a cross-section. It is sometimes desirable to give more width to the platform by not attaching the beams to the pole, but supporting them on cross-members, see Fig. 271. The same theory holds true however, *i.e.*, sufficient bolt bearing area must be provided to carry the load, either in beam bolts, cross-beam support bolts, or brace bolts. It may be possible in some cases to gain some support by setting the beams or cross-beam supports into "gains" in the pole but this practice is usually not an advisable course, for if the gains are made deep enough to be of much assistance, the pole may be considerably weakened.

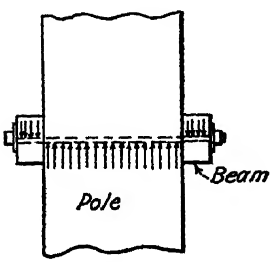


FIG 267.—Distribution of bearing stress for platform support.

In some cases of long platforms or those with unusually heavy loading, more than two poles are used as supports.

3. *The strength of the poles* must be sufficient to sustain the load as columns. Platforms are usually built as near to the ground as proper clearance permits, *i.e.*, 12 to 20 ft. above ground, and, the effect of slenderness ratio is not so marked as for cross-arm installations. The soil bearing under the pole may sometimes require attention if the loads are very heavy.

4. *Stability.*—Cross-bracing between beams and knee bracing from beams to pole are sometimes advisable, especially with long platforms, in order to keep the structure from twisting out of shape. Intermediate spacer blocks between the beams, if prop-

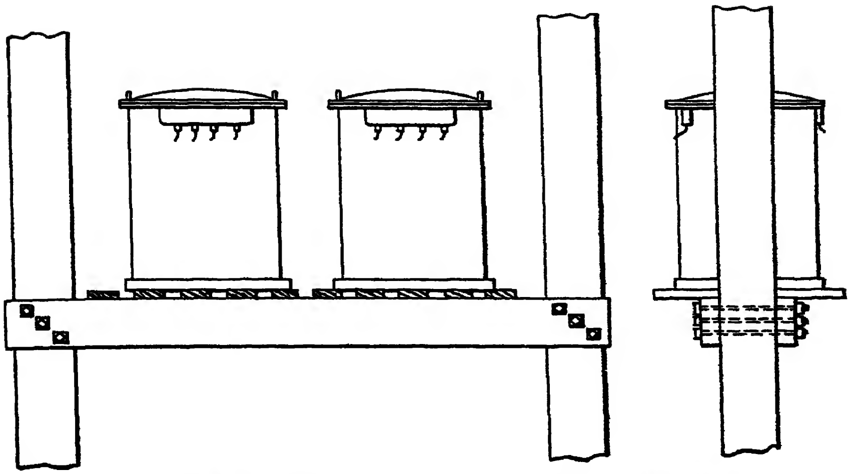


Fig. 268.—Simple wooden platform—no bracing.

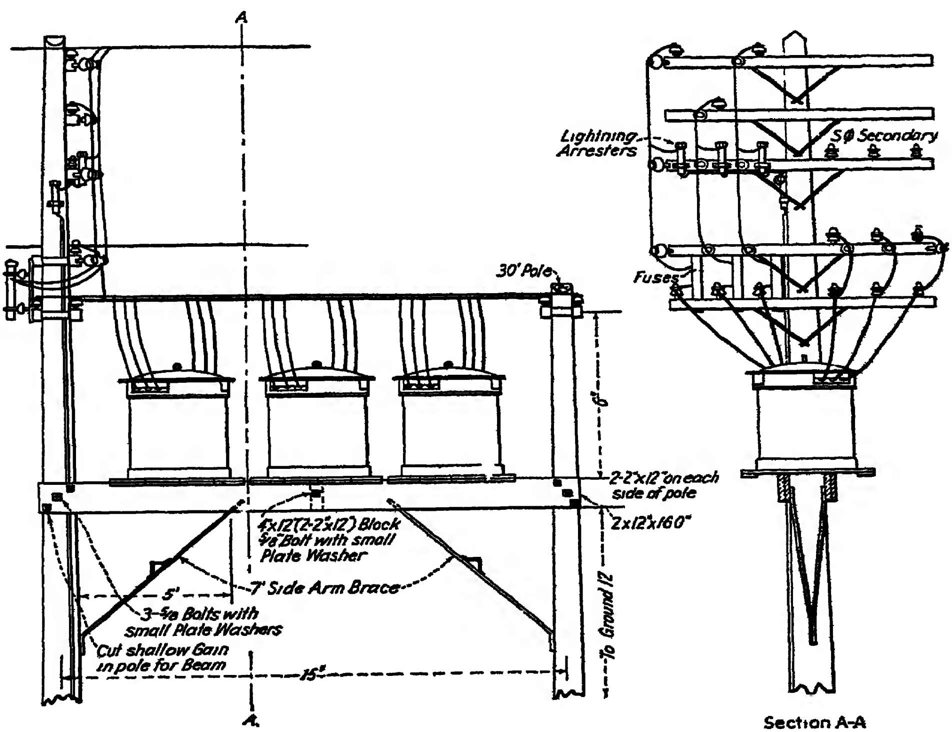


Fig. 269.—Wooden platform braced with side-arm braces.

erly placed, increase the stability as well as maintain the proper spacing.

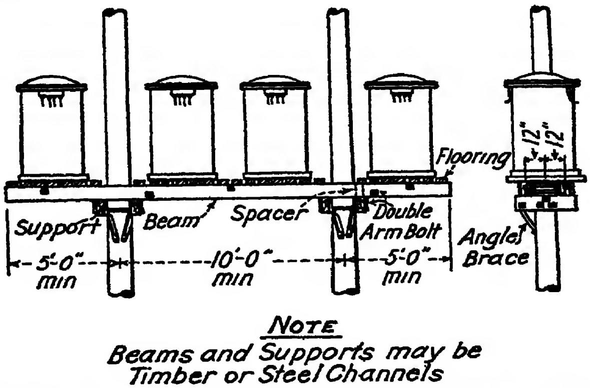


FIG. 270—Platform suggested in N.E.L.A. Overhead Systems Reference Book.

There are many variations of the methods of obtaining the strength required at the points mentioned above.

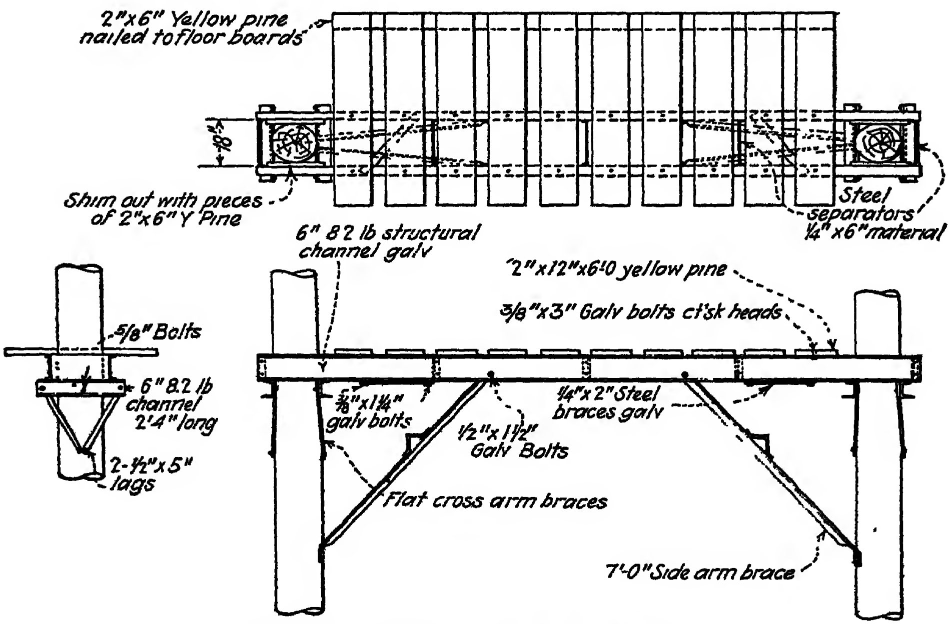


FIG. 271.—One type of steel platform.

Figures 268, 269, 270, and 271 give some typical examples of platform construction. Figure 272 is a small platform built

on a single pole for supporting a single transformer. It is often useful with side-arm construction.

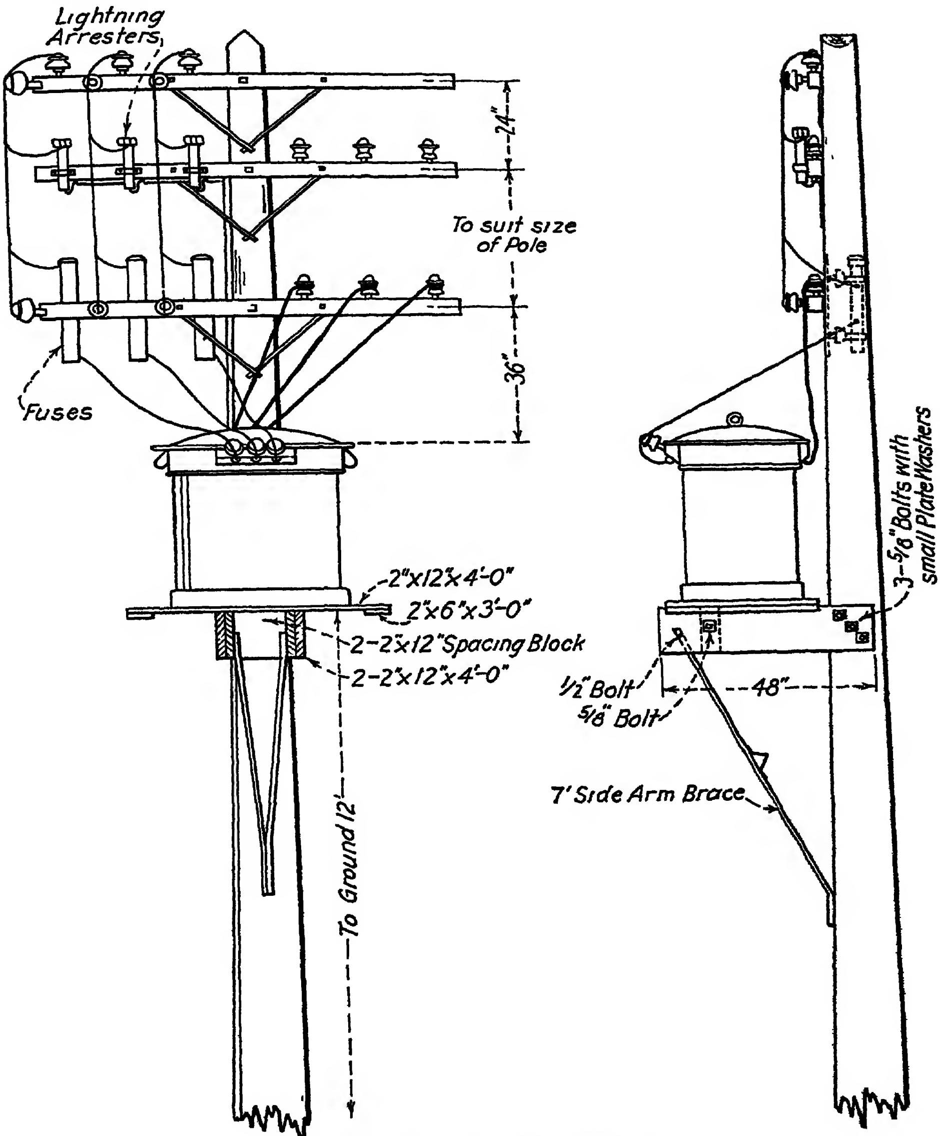


Fig. 272.—One-pole platform.

Accessories.—*Fuses* are usually used between the transformer and the primary line. They may often be conveniently mounted

on the same cross-arm on which the transformer is carried Figure 263 indicates such mounting. Figure 264 shows them mounted on a separate arm for a three-phase transformer in order to gain clearance for the primary leads from fuse to

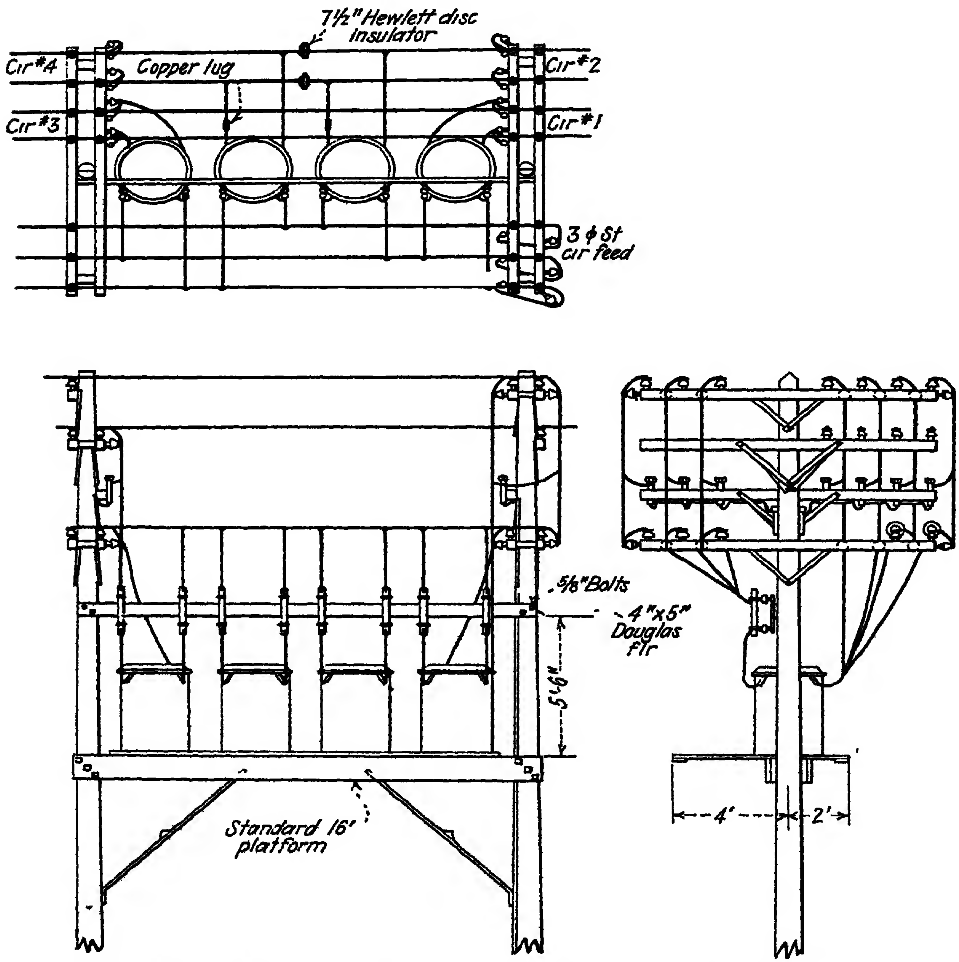


FIG. 273.—Street-lighting transformers on platform, showing fuses mounted on beam

transformer. On platform installations it is sometimes necessary to fuse each transformer separately. Figure 273 shows the fuses mounted on a beam over the transformers.

Lightning arresters are quite commonly installed in connection with transformers. They are indicated on Figs. 263 and 264.

It is often convenient to mount them on the primary line arm close to the line to which they are connected, but some choose to mount them on separate cross-arms for better clearance. This is almost necessary for the large arrester used with higher voltages (6,600 and over). Some engineers prefer to mount them as close to the transformer as possible, often on the hanger arm, on the assumption that better protection is thus afforded. It is probable that on account of the short length of the trainer wire compared with the speed of a *lightning* surge, it will not make appreciable difference in the protection at which point the arrester is mounted.

Trainer wires are shown on the various drawings of transformer installations given. Trainers should be kept in either horizontal or vertical runs, not crossing the pole at an angle, should be held taut on insulators, with intermediate supports where the vertical drop is over about 8 or 10 ft., and should have the clearances from other wires and equipment as specified in Chap. XXIII.

Grounding.—Although the subject of grounding does not belong exclusively to transformer installations, it is included here because more grounds are usually installed in connection with transformers than elsewhere on a distribution system. Lightning arresters must of course be well grounded, with as direct a connection to ground as possible. It is customary to ground the neutral or midpoint to a three-wire, single-phase secondary and also some point on a three-phase secondary if the voltage is not over 230 volts or thereabouts. Some companies make it a practice to ground transformer cases also. The electrical features of grounding were discussed in Chap. XIII.

The best ground is usually a water system but this is often not available near a pole line. A well casing or similar connection is also a good ground as a rule where available. For arrester grounds, dependence must usually be placed on driven pipes or rods and for grounding secondary neutrals these are also quite commonly used, even where water-pipe grounds are also present on customers' premises.

Soil conditions are so variable both with location and also with seasons that few definite rules can be given as to how a driven ground should be made. The only really satisfactory method is to test the ground resistance from time to time and if it is too high, take some measure to reduce it. The recommended maxi-

mum resistance of grounds as given by the Safety Code and the National Electrical Code is as follows:

For water-pipe connections, 3 ohms.
For buried or driven grounds, 25 ohms.

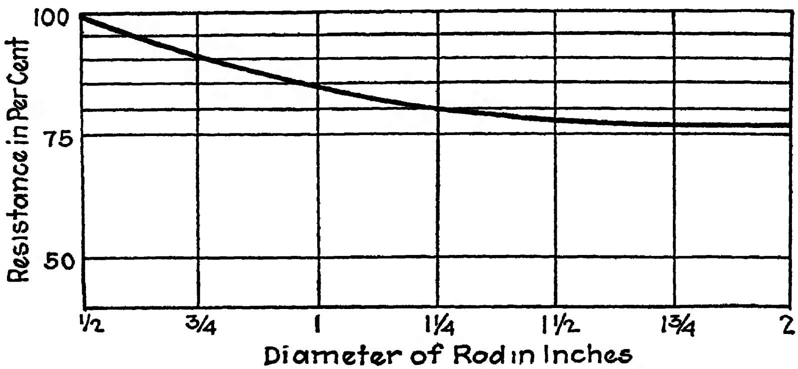


FIG. 274.—Approximate variation in resistance of ground connection with diameter of rod

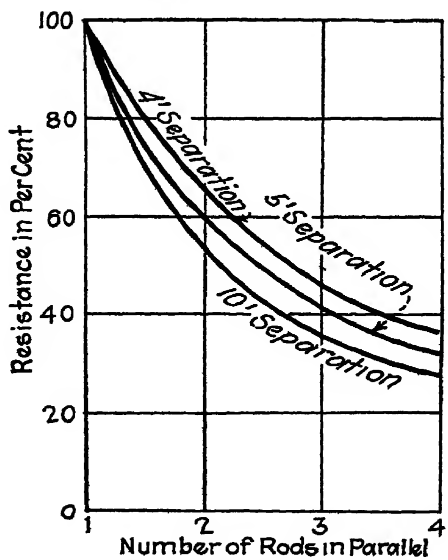


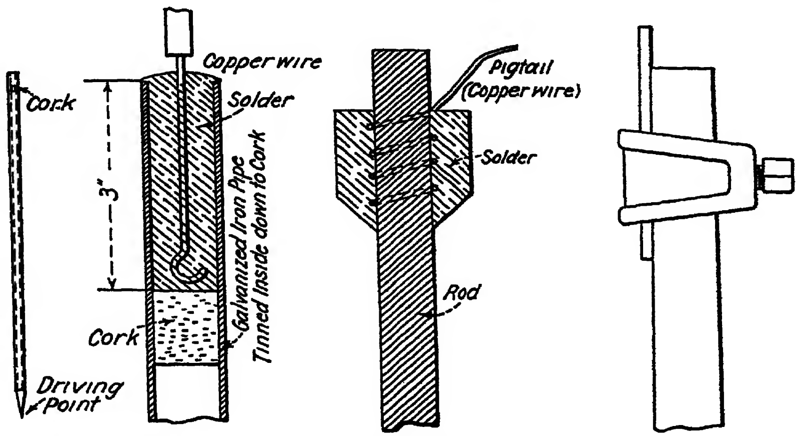
FIG. 275.—Approximate variation in resistance of ground connection with number of rods.

Ground rods for driven grounds are made of galvanized pipe, galvanized solid-steel rod, or copper-covered steel rod—the first and last types being the most commonly used. They vary in diameter from ½- to 1-in., pipes being ordinarily about ¾ in.

and solid rods from ½ to ¾ in. In length, they vary from 4 to 10 ft or more, with the 6- and 8-ft. lengths the more common

The resistance of a ground is not proportional to the diameter of the rod. A large part of the total resistance occurs in the soil surrounding the rod, hence the diameter of the rod is relatively unimportant. A ½-in. rod is only a little higher in resistance than a ¾-in. rod. Figure 274 shows an approximate curve of variation of total resistance with diameter.

The length of rod necessary is, of course, dependent to quite an extent on the depth at which moisture is found in the soil. Lengths less than 6 ft. are rarely advisable, while lengths over



(a) Pipe and Connection to it (b) Pigtail Soldered on in Shop (c) Clamp

FIG 276 —Connections to ground rods.

10 ft. are relatively hard to install. An 8-ft. length is quite satisfactory for average conditions where the soil is not unusually dry.

The resistance of the ground may be reduced by installing more than one rod. Figure 275 indicates approximately the variation of resistance with number of rods. Rods should not be installed close together. A separation of at least 1 ft. should be used and more is preferable up to 4 or 5 ft. where possible.

Treating the ground around the rod to decrease its resistance is often resorted to. This consists of salting the rod with common salt, calcium chloride, copper sulphate, etc., or packing coke or charcoal around it. The salting is for the purpose of attracting and retaining moisture, thereby increasing the conduc-

tivity of the soil. It is sometimes done by digging about the rod for a foot or so radius and a foot or so depth and filling the hole part full of salt. sometimes by placing the salt in a vertical

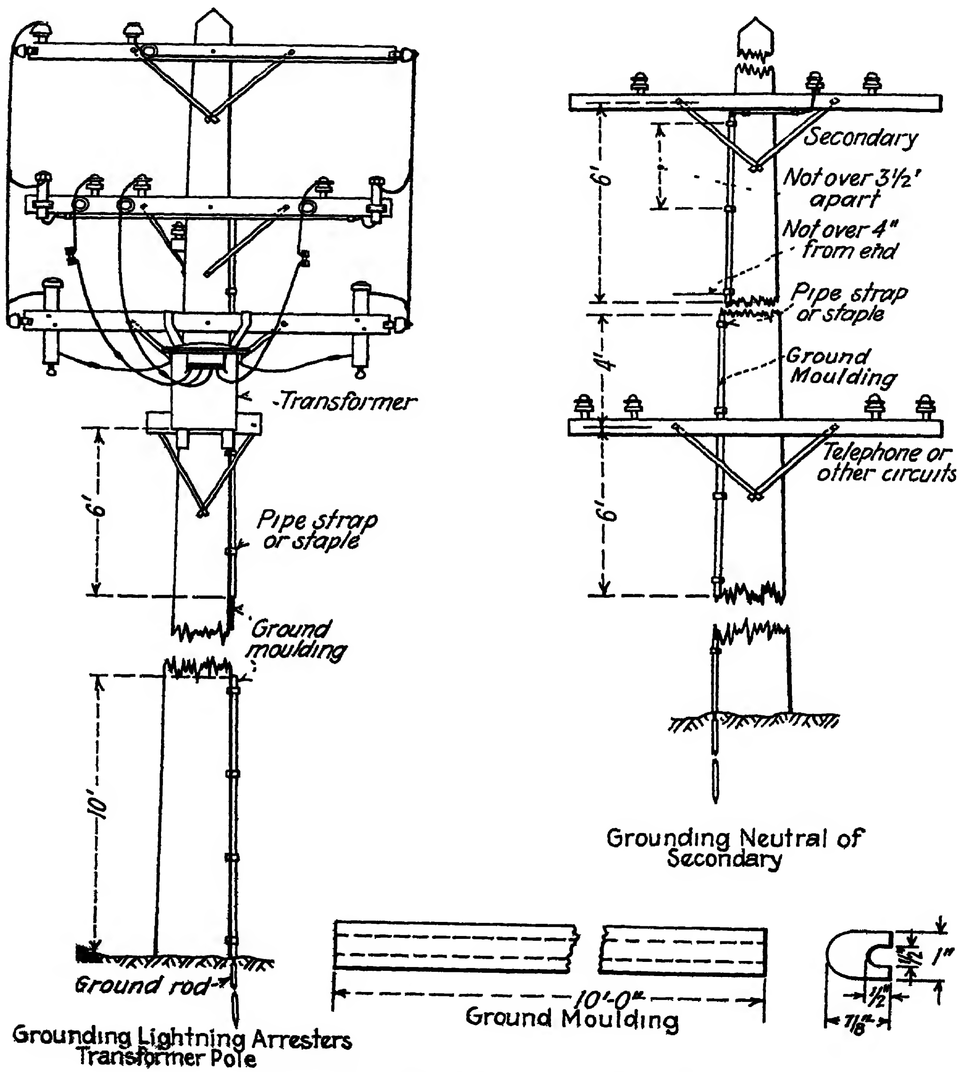


FIG. 277 —Use of ground moulding

pipe or tile alongside the rod. One objection to salting is that the salt dissolves and leaches away in time, requiring renewal at regular periods if its effectiveness is to be maintained. Another

is that some kinds of salt, such as common salt (sodium chloride), are likely to increase corrosion of the rod Copper sulphate is free from this objection but is quite expensive. The action of coke or charcoal is to increase the effective conducting volume rather than to attract or retain moisture. Coke is subject to the objection that it is likely to have a sulphur content which will increase corrosion in the rod, even a copper rod Charcoal is free from this objection

The connection to the rod should be carefully made Copper wire (not smaller than No 6 and preferably larger) should be used down the pole and either a soldered or solid clamped connection made to the rod A field job of soldering the wire to the outside of the rod after it is driven is difficult and usually not satisfactory Figure 276 (*a*) shows a connection used with good results with a pipe. The end of the pipe should be tinned inside and corked before being taken out on the job. Figure 276 (*b*) shows a pigtail soldered on the rod in the shop, connection being made to the pigtail in the field. Figure 276 (*c*) shows a clamp connection used with copper-covered steel rods.

The ground-connecting wire down the pole should be covered with an insulating covering, usually a wooden molding, for at least 8 or 10 ft up from the ground as a protection to the public (Safety Code specifies 8 ft). It should also be similarly protected where it passes through space occupied by communication circuits or other supply circuits or equipment, a good practical rule being to cover it from at least 6 ft. below to at least 4 ft. above such conductors, see Fig 277

CHAPTER XXVI

UNDERGROUND CONSTRUCTION

It was stated previously that in this book it was intended to stress particularly overhead line construction as being the most commonly used. It is felt, however, that for the sake of completeness some attention should be given to the major features of underground construction. These cannot be covered in any great detail—to do so would require a volume in itself and the subject has been treated in other books such as "Underground Transmission and Distribution" by E. B. Meyer, and "Underground Systems for Electric Light and Power," by F. C. Ruhling It is intended only to indicate some of the chief points to be considered in underground work.

Conduit.—Probably the majority of underground cables installed in this country are installed in conduit. Cable so placed is much more convenient to work with in locating faults and making repairs, especially in congested districts.

The choice of location of a conduit to be run in a street or alley should be such as to conform best with the following requirements:

1. To avoid where possible surface obstructions to digging the trench, such as trees, poles, posts, fire plugs, etc.
2. To avoid subsurface obstructions to the trench and the conduit itself, such as gas piping, water piping, steam piping, sewers, conduit of other utilities, tunnels, vaults, etc., see Fig. 278.
3. To avoid cutting pavements more than is necessary.
4. To avoid as much as possible obstructing street traffic during construction and in future work in and around manholes
5. To avoid curves and bends in the conduit as far as possible.
6. To avoid injury to the conduit by other utilities in maintaining their property.

Ducts vary in size from 2 to 5 in. in diameter, 4 in. being a commonly used size which is suitable for most of the cable ordinarily used in distribution. The number of ducts used in a conduit run depend on the requirements and the space available. It should be kept in mind in choosing the number of ducts and

their arrangement, that interior ducts cannot be used to full advantage on account of their smaller heat-radiating capacity, unless special means of ventilation is adopted.

Figure 279 shows typical arrangements of ducts of various numbers in a conduit. The ones marked "ordinary" are the preferred arrangements, the "special" ones being used where space is limited or other conditions make it desirable. The figures in the duct positions indicate the continuity of each duct if change is made from one arrangement to another between man-

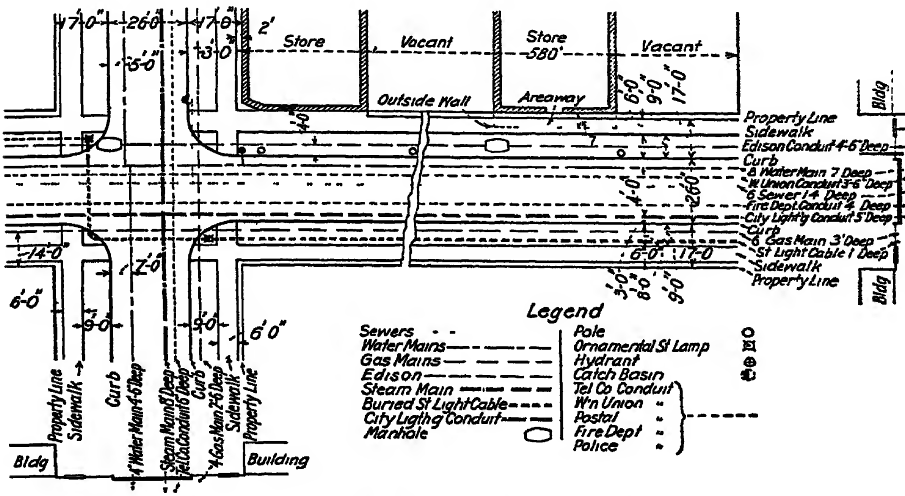


FIG. 278.—Subsurface obstructions to conduit.

holes, a duct going from position 1 in one arrangement to position 1 in the other, etc.

Figure 280 indicates the spacing and arrangement of ducts used by one company at entrances to manholes, the change from the arrangement in the run being made in order to facilitate the training of cables around the manhole walls, by spreading them somewhat. The change should be made gradually, starting at least 6 ft. back.

Conduits are constructed in several different ways as follows:

1. Tile ducts with an envelope of concrete around the outside of the conduit.
2. Fiber ducts cast in a body of concrete.
3 Monolithic conduit with the ducts formed by coring

The concrete used for the envelope and between the ducts may be satisfactorily made in the following proportions: 6 parts

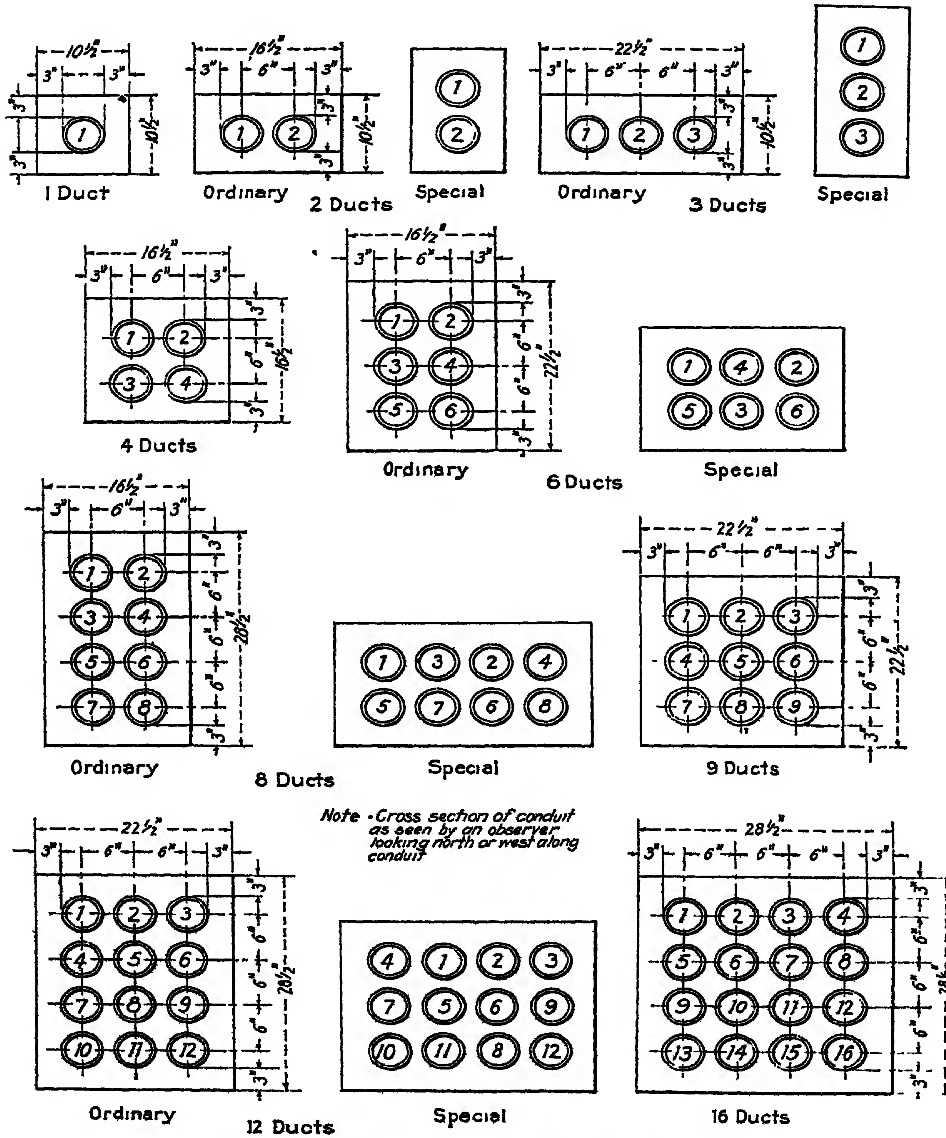


FIG 279.—Arrangement of ducts in a conduit.

gravel (1 in. screen), 1 part Portland cement or 6 parts 1-in. crushed limestone, 3 parts sand, 1 part Portland cement.

Figures 281 and 282 indicate typical cross-sections of tile and fiber duct conduits.

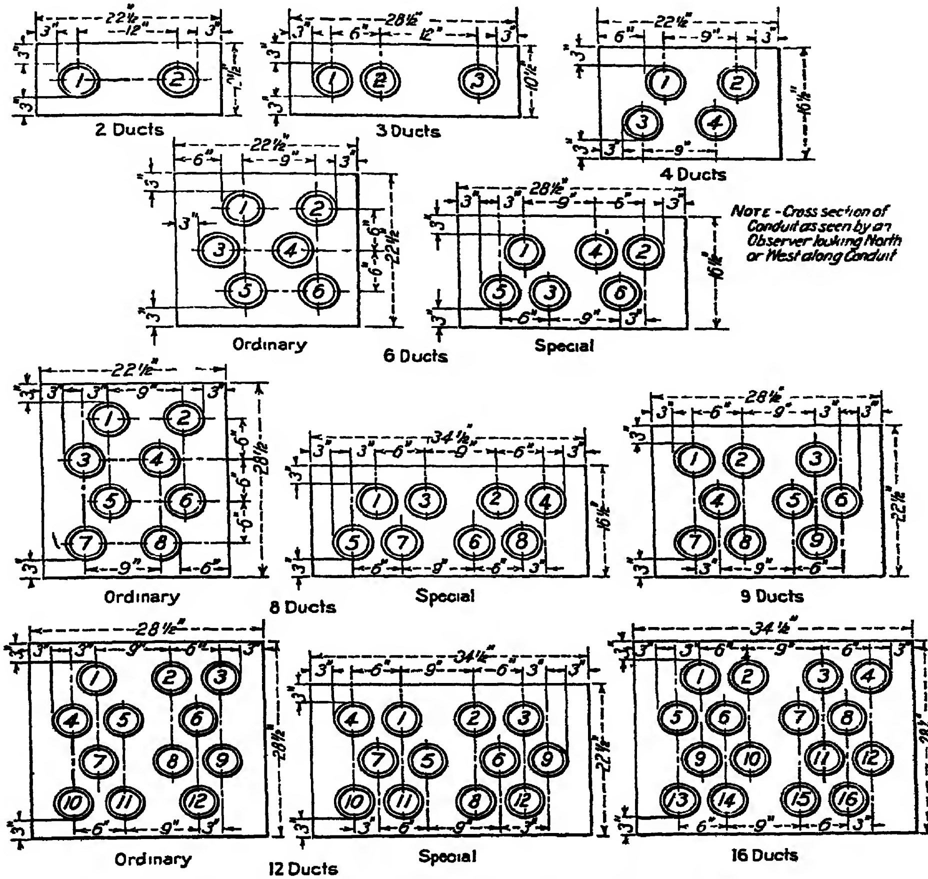


FIG. 280.—Arrangement of ducts at manhole entrances.

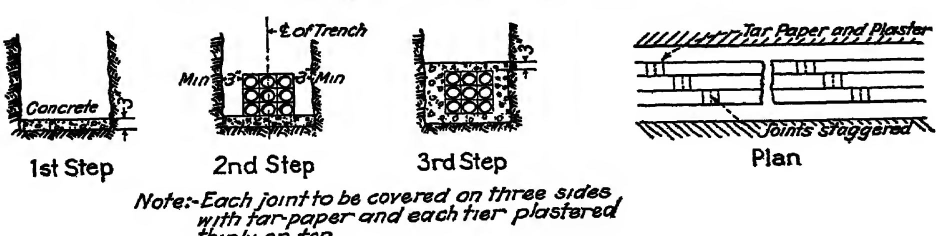


FIG. 281.—Construction of clay (tile) duct conduit.

Fiber conduit is probably more used at present for electrical distribution than either of the other types.

The *depth* of the conduit below the surface should be sufficient to avoid interference by shallow excavations, driven points, etc. The following minimums to the top of the conduit are suggested:

	Inches
Below pavement (surface)	30
Below dirt surface paralleling pavement (including similar locations on streets as yet unpaved)	36
Below unpaved street or alleys (allow for 30 in. below probable future pavement grade)	36
Below sidewalks	36
Below dirt surface on private rights-of-ways, customers' premises, etc.	30
Below driveways on private rights-of-ways, customers' premises, etc	36
Below street-railway tracks (base of rail)	24
Below steam or electrified railroad tracks (base of rail)	42

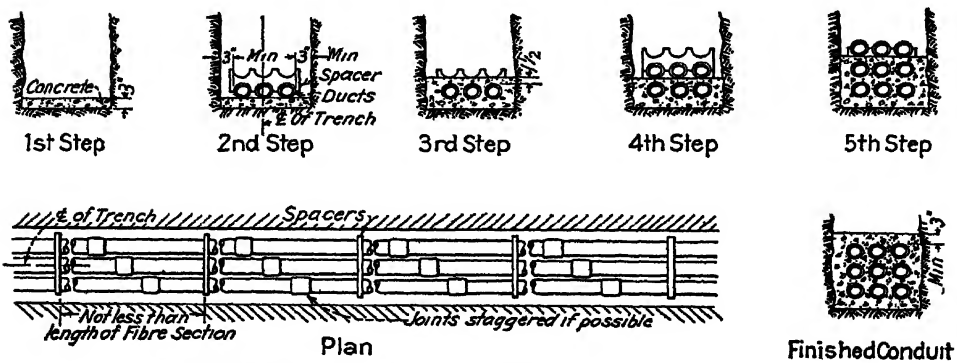


Fig. 282.—Construction of fiber duct conduit

Naturally much greater depths than these will often be necessary to avoid obstructions or to maintain a grade.

The conduit should be graded evenly from manhole to manhole, at a slope of not less than 4 in. per 100 ft. Grading both ways to manholes from a high point in between should be avoided if possible.

The excavation for the trench should be so made that the conduit will rest on solid undisturbed earth. If the earth is soft or yielding, it is often advisable to use steel reinforcing in the concrete envelope on the bottom of the conduit.

When fiber duct is used it is sometimes laid up tier by tier on spacers, the concrete being poured on each tier before the next is added. Another method is to lay up the whole duct structure with horizontal and vertical spacers, tie it in place, and pour the concrete afterward. Figure 282 shows the steps of the first method.

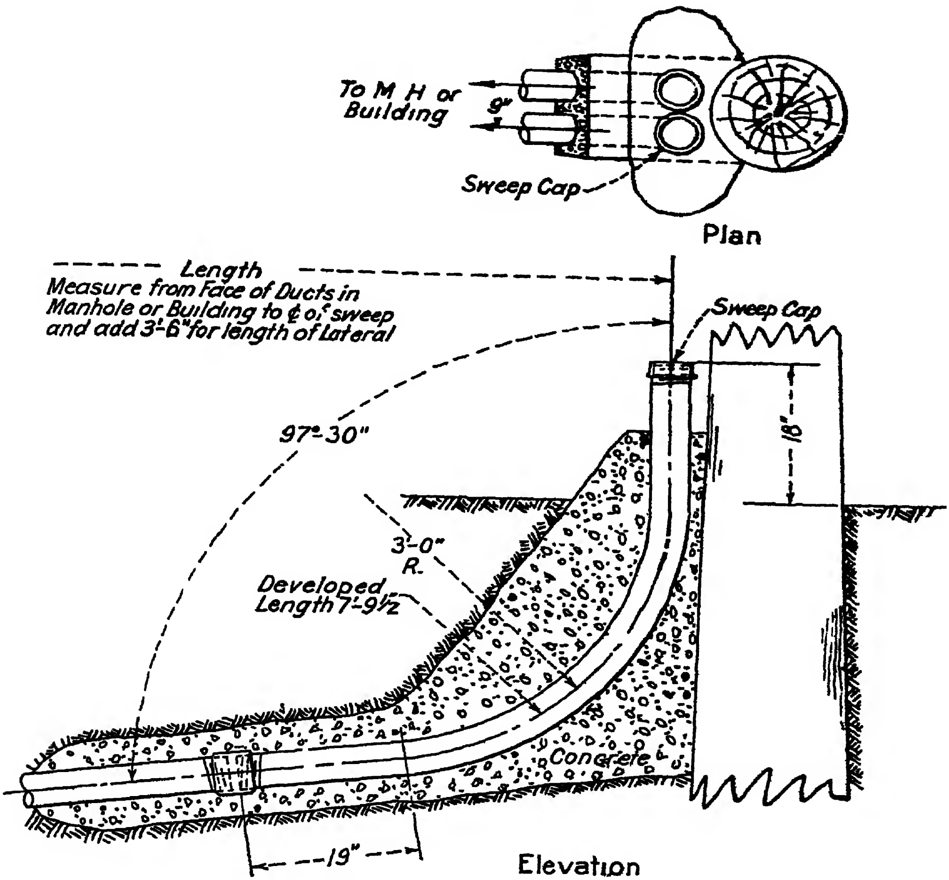


FIG. 283.—Sweep.

Laterals to cable poles, where the cable goes to the overhead, usually terminate in 90-deg. bends of fiber or iron pipe (called "sweeps"). Such an installation is shown in Fig. 283.

Manholes.—Manholes must be placed along the conduit at such distance apart that the cable may be conveniently pulled in between them. It is well in locating manholes to consider

possible branch or intersecting lines of conduit, placing the manholes where they can be used for such lines if necessary.

Manholes are built of various sizes and shapes, according to the purpose for which they are intended. Probably the most common form for general use in handling cables is the elliptical,

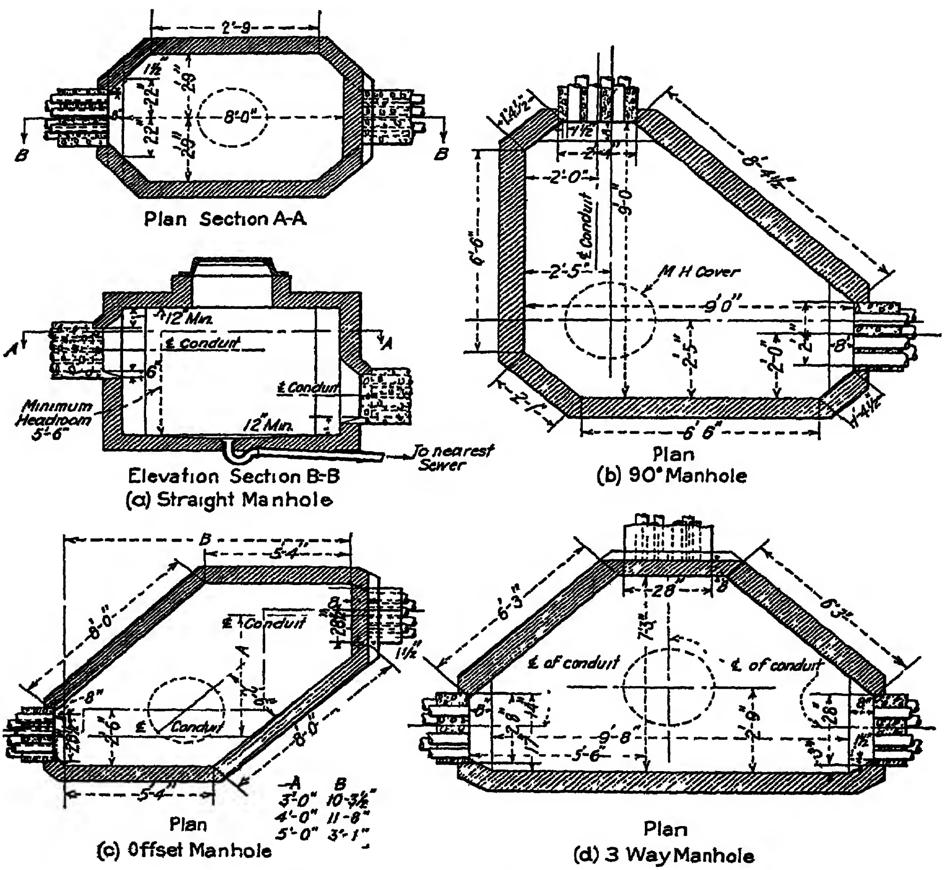


FIG. 284.—Typical manhole shapes.

either with curved sides or eight-sided of similar general shape. The cables enter at the end and train around the walls on either side. Such a shape is indicated on Fig. 284. Other shapes whose purpose is evident are also shown on Fig. 284. Manholes for installation of transformers or other such equipment must usually be larger and specially shaped for the purpose.

The manhole should be deep enough to allow the lowest duct to enter not less than 1 ft. above the floor. The headroom should be sufficient to allow the highest duct to enter not less than 1 ft.

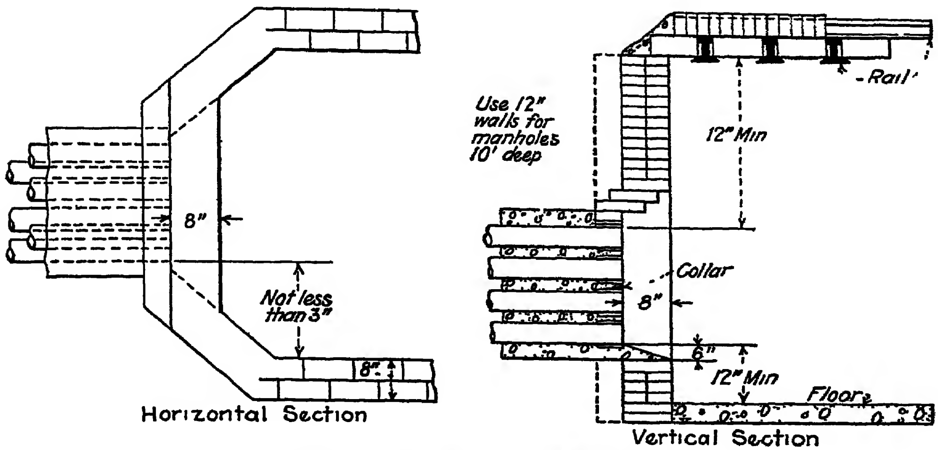


Fig. 285 —Typical brick manhole wall.

below the ceiling The clear headroom for working conditions should be at least 5 ft., 6 in. in manholes where frequent work is done and at least 4 ft. in any type

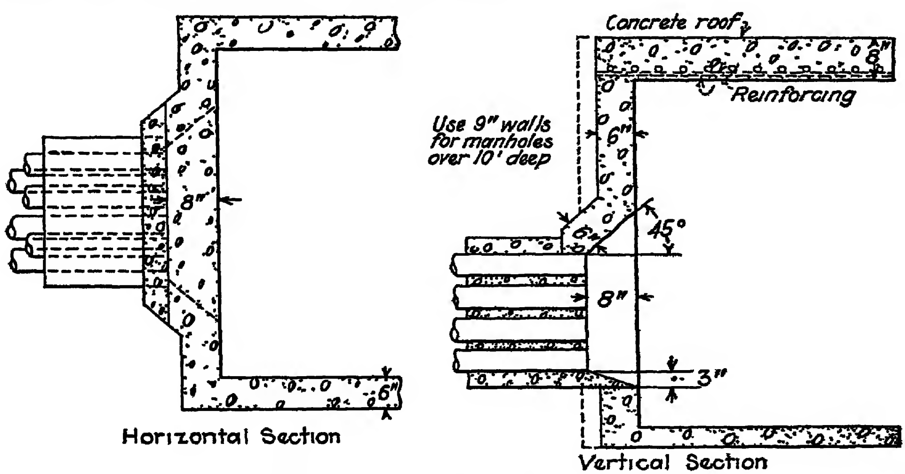


Fig. 286.—Typical concrete manhole wall.

The bottom of the manhole should be high enough that a *drain* to an adjacent sewer system will be effective in keeping it free from water The drain should have a slope of at least 0.4

ft. per 100 ft. toward its outlet and of not smaller than 4-in. tile. Where direct drains to a sewer are not feasible, a drain to an adjacent manhole which can be directly drained may sometimes be carried underneath the conduit. Where drains cannot

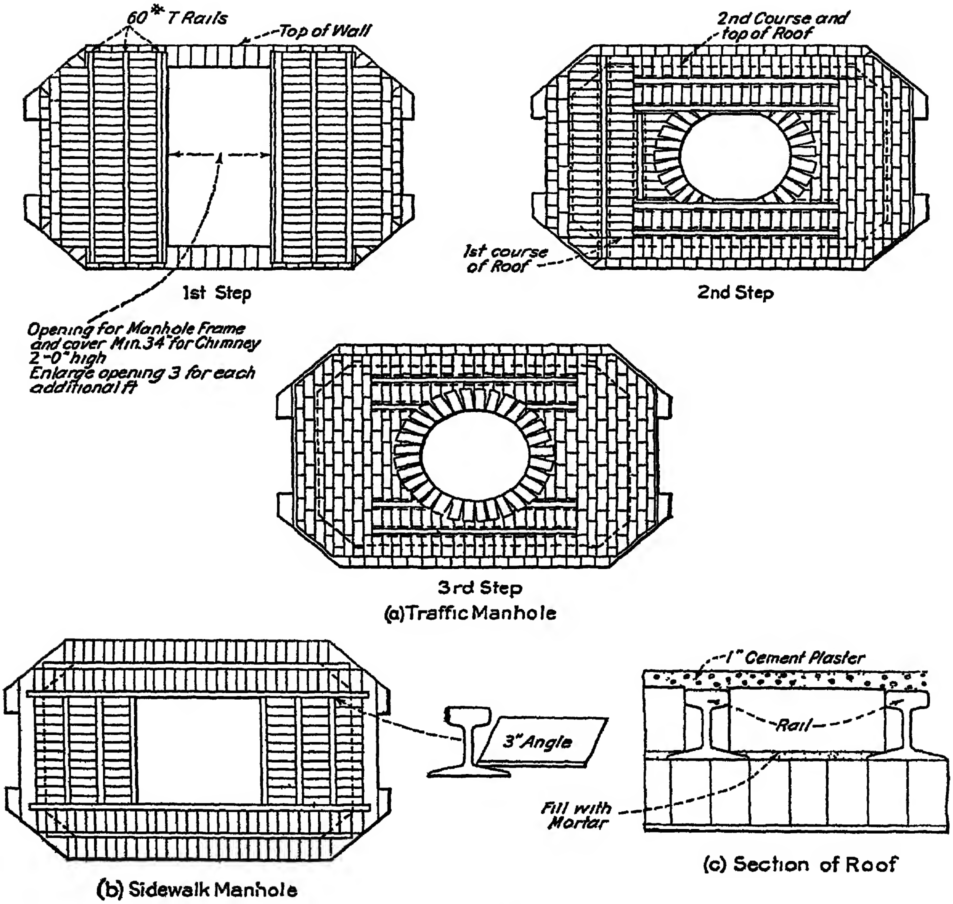


FIG. 287.—Typical brick roof

be used, sumps are sometimes installed under the manhole floor to care for ordinary seepage, etc.

The *floor* of the manhole is usually made of concrete and should be not less than 4 in. thick.

The *walls* of the manhole may be built of brick, concrete, concrete block, etc. Brick walls should be at least 8 in. thick for

manholes near the surface (say not over 10 ft. deep) and 12 in. for deep manholes Figure 285 shows a brick-wall manhole.

Concrete walls should be not less than 6 in. thick for manholes near the surface and 9 in. thick for deep manholes. It is advisable

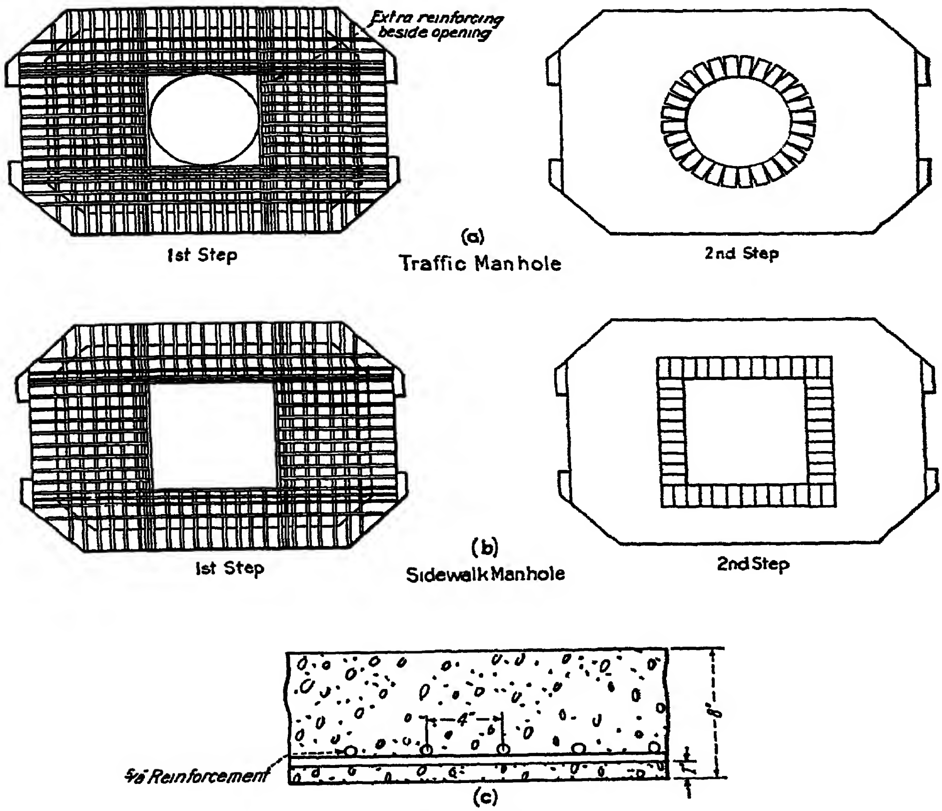


FIG. 288 —Typical concrete roof

to include some steel reinforcing in the walls, especially for large manholes. Figure 286 shows a concrete-wall manhole. Concrete walls must be built with the use of forms. Collapsible forms are sometimes made which can be used repeatedly. One objection to concrete walls for manholes is that they must be allowed a certain time to harden and in streets where traffic is heavy, the delay is sometimes a disadvantage.

Conduit entrances should be constructed with the object of facilitating the training of cables. Figure 285 indicates one type

of entrance. Porcelain duct bells are sometimes used at the end of the ducts to form a smooth surface which will not damage the cable.

The *roof* of the manhole is sometimes made of brick carried on steel (old rail is a convenient form), or of reinforced concrete. Figure 287 shows a brick roof, Fig. 288 a concrete roof. The concrete roof is subject to the same objection as the concrete wall.

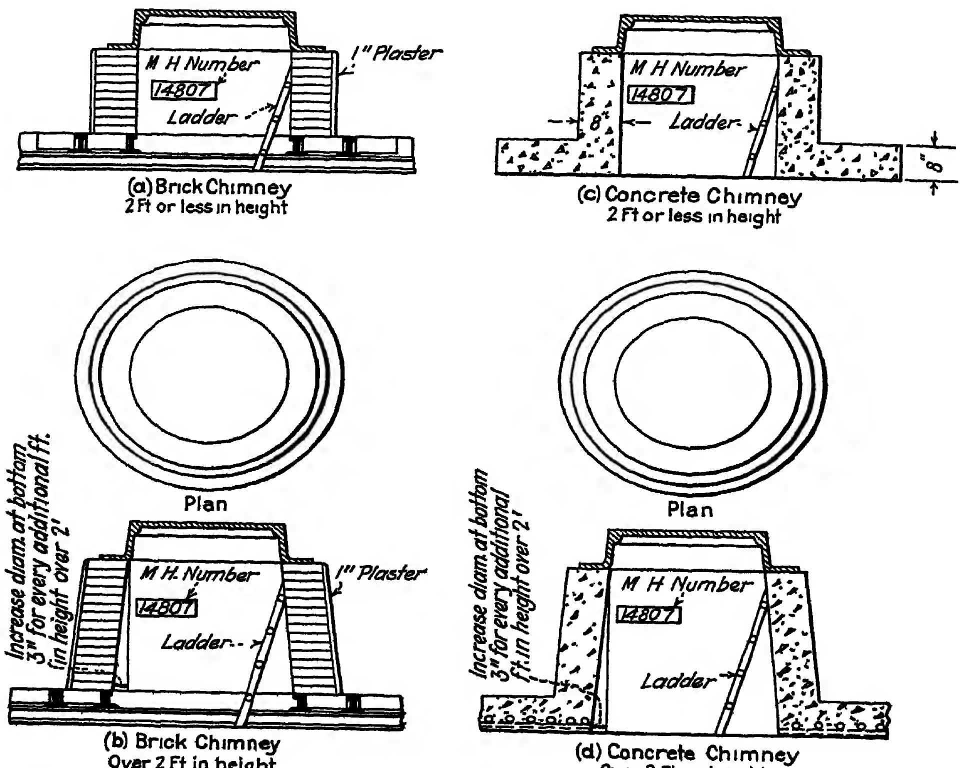


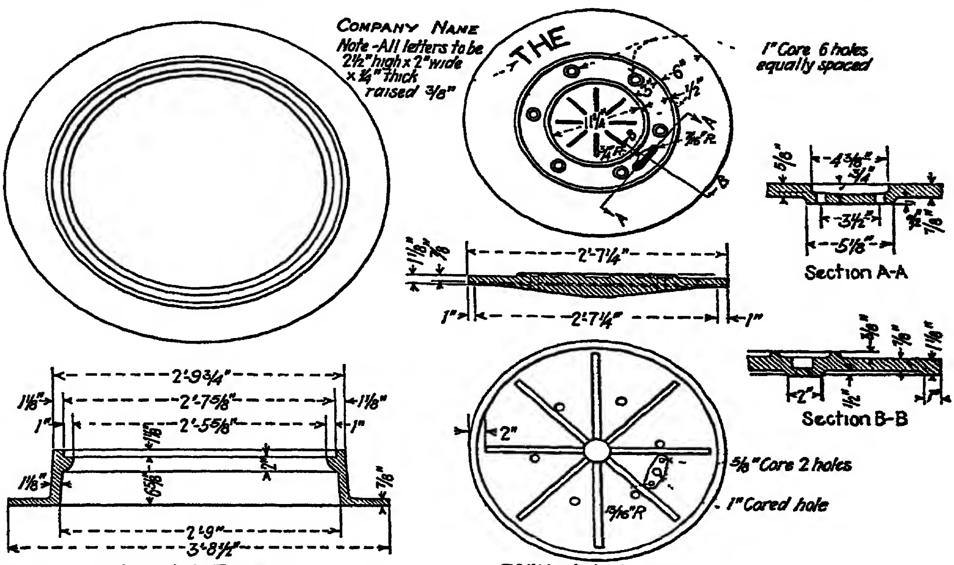
FIG. 289.—Typical chimney

An opening must be left in the roof for access to the manhole. A *chimney* connects the manhole with the surface. This chimney may be built of brick or concrete, not less than 6 in. thick. It should be of such a diameter as to accommodate the cover to be used at the surface, and if of any considerable height, should taper somewhat. Figure 289 shows a typical chimney.

The *cover* used at the surface is usually made of cast iron, malleable iron, or steel, and set in a frame of similar material.

Sometimes covers which are infrequently removed are made of reinforced concrete. The cover should be not less than 26 in in diameter to allow easy access for a man, and 30 in. is a preferable size. Larger sizes are sometimes necessary to allow access of equipment such as transformers. A typical cover is shown on Fig. 290.

Cable standards or racks bearing arms for supporting the cables are attached at intervals along the walls A maximum spacing



30" Manhole Frame C I 30" Manhole Cover C.I.

FIG. 290.—Typical manhole frame and cover

of 4 ft. is usually advisable. They should be placed so that the bottom cable is 12 in. at least above the floor and the top cable at least 12 in. below the ceiling. These standards are made of cast iron, malleable iron, or steel and are of various designs. Figure 291 shows a typical installation.

Another essential piece of equipment for a manhole is a ladder, usually made of galvanized steel.

Figure 292 shows a perspective of a typical brick manhole.

Cable.—Lead-covered cable is the most generally used for underground construction, although cables with non-metallic sheaths are used to some extent. The insulation around the conductors may be of impregnated paper, rubber, or varnished cambric. Paper-insulated cables are probably more usual for

primary voltages. For secondary voltages paper insulation may be also used, particularly in long runs, such as direct-current feeders, but where the ends are exposed, as at service entrances or in junction boxes, unless sealed in some way moisture is likely to enter and damage the insulation. Rubber-insulated cables are more suitable for such purposes.

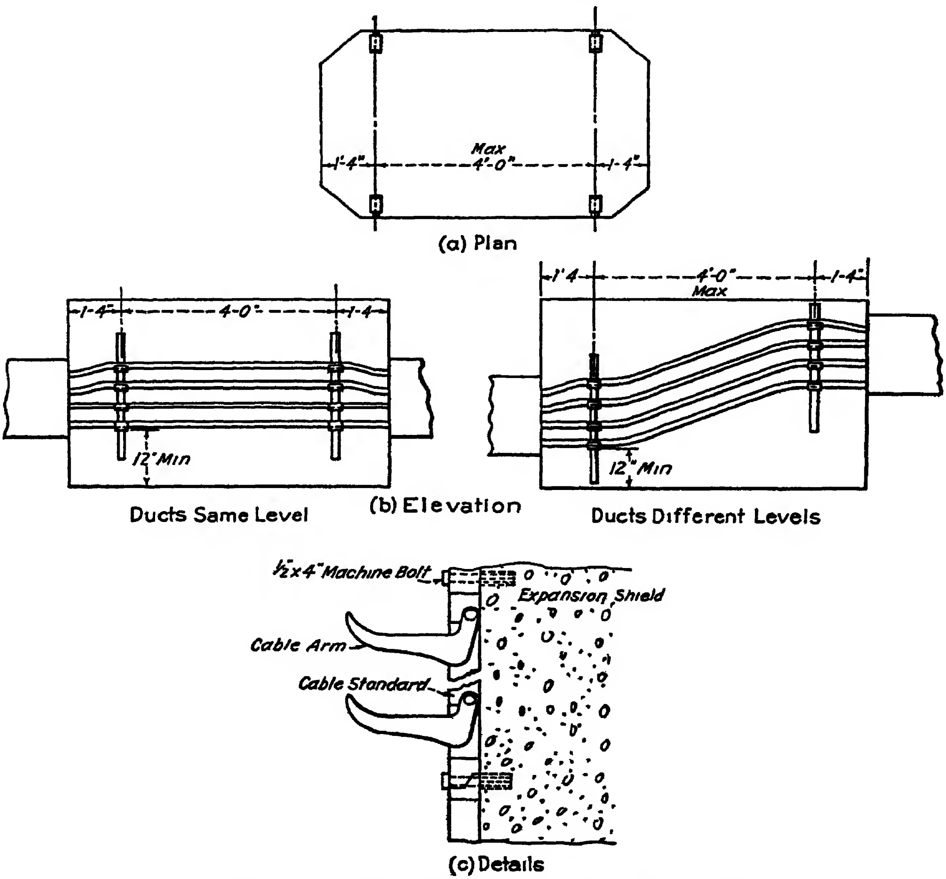


FIG. 291.—Typical installation of cable standards.

Single-conductor cables are used where the conductors are very large, such as direct-current feeders and large mains, for street-lighting circuits, for feeding distribution transformers, and for secondaries in many places in connection with secondary networks, and other underground distribution where numerous branch joints are made. Some attention must usually be paid to

induced voltages and currents in the metal sheaths when single-conductor cables are used with alternating current. This difficulty is avoided with multiple-conductor cables and such are generally preferable where they can be conveniently used.

Installation.—Every precaution should be taken in installing a cable in a duct run that the sheath is not abraded or otherwise

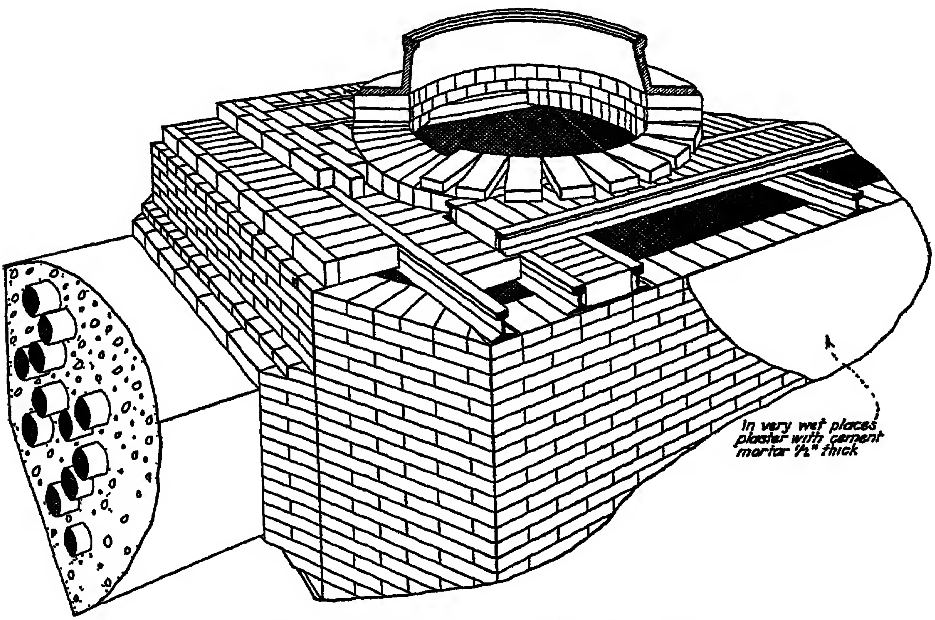


FIG 292.—Perspective of typical brick manhole.

injured. The surface should be lubricated to facilitate pulling into and out of the duct—grease or soapstone are used for this purpose. Short kinks or bends in the cable, should be avoided, *i.e.*, any bends should have a radius not less than 12 in. for cables less than 1 in. in diameter and 20 in. for larger cables.

Where buried cable is used (not in conduit) the cable is usually protected by an armor of steel tape or its equivalent. It is buried in a trench, preferably at least 2 ft. deep, and is often further protected from damage by laying timbers or slabs of concrete over it. It is a good plan on long buried cables to place monuments or markers of some sort at the surface over the cable, especially at corners and bends, to mark its route and facilitate the finding and repairing of faults.

Street-lighting cable in parkways between lamps is sometimes installed by pulling it in behind a special plough which forms a channel ahead of the cable and pushes the earth back in place over it.

Joints.—Care in the making of cable joints is effort well repaid. Carelessly made joints are likely to be sources of trouble in causing failures and hence interruptions to service. The instructions below are quoted from the construction specifications of one company and are given as indicative of the precautions which should be taken and also the methods of carrying out the operations necessary in making up a joint:

INSTRUCTIONS FOR MAKING 4,800-VOLT CABLE JOINTS

Every cable splicer shall familiarize himself with the instructions given in the following paragraphs before working on any 4,800-volt cable joint

1. General Precautions.—The following general precautions shall be observed in making joints in 4,800-volt cable.

When *cutting and removing the sheath,* belt insulation, fillers, etc., the utmost care shall be exercised to prevent cutting into or otherwise injuring the insulation to be left on the cable.

All sharp edges or projections which might tend to penetrate or cause air pockets in the insulation shall be carefully removed from sheath bell, conductors, copper-splicing connectors, etc. Great care must be taken not to file or nick the conductor itself in doing this.

Belling of sheaths, spreading of conductors, and *similar* operations shall be done with fiber wedges and not with steel tools to prevent possible damage to insulation

Every precaution shall be taken *to prevent any filings, dirt, or moisture* being included in the insulation of the joint. A very small amount of any of these is likely to cause failure of the joint when it is put into service. To this end be very careful to keep the hands and all tools and containers used clean and dry, not to expose insulating materials to the atmosphere more than necessary, to wipe off all surfaces carefully when there is any chance of their having accumulated dirt or moisture, using a clean cloth for this, and to heat insulating compound to the proper temperature for pouring over insulation or filling the joint. (250°F. for tape-impregnating compound and for pure paraffine for joint filling, measured by thermometer.)

The greatest care should be observed in *applying hand-wound insulation* to leave no air pockets which are possible sources of trouble in the finished joint. To this end all surfaces of conductor or factory insulation shall be carefully smoothed, insulating tape drawn tightly in winding, with especial attention to getting uniform lap and avoiding wrinkles, and tape-impregnating compound used freely on each layer to fill all possible voids. When applying tape in a direction opposite to the winding of the factory tape, the latter shall be drawn tightly and held with one hand until the first layer is applied.

Conductors should be spread as little as possible in making up the joint in order to avoid the possibility of movement or wrinkles in the insulation

In filling the joint with paraffine be sure that the paraffine is hot (250°F. measured by thermometer), that all air bubbles have passed off and the paraffine comes out clear before stopping, that the joint has cooled sufficiently before the next filling is made, and that sufficient number of fillings are made to completely fill the joint.

On account of close quarters in a manhole and the difficulty in readily seeing all parts of the joint, *use the little mirror* very freely for *careful inspection* during various stages of making up the joint

Remember that a little precaution will avoid a multitude of failures and possible embarrassments, and is infinitely easier than the repairs and replacements which are sure to follow its omission.

Details of Operations (2 to 26, inclusive)

Under each of the types of 4,800-volt cable joints covered in the drawings and accompanying instruction sheets . . . the operations necessary in carrying out the work are indicated. The following paragraphs give in more detail the methods to be used and precautions to be observed in performing each of these operations where complete details are not given on the instruction sheet for the particular joint. Numbers given on these instruction sheets in connection with the various operations refer to the number of the paragraph herein in which that operation is described. All operations shown on the instruction sheets are not repeated here, hence *the instruction sheets and not these details of operations must be followed in making up a joint.*

2. Train Cable.—Make the necessary bends *only* and place the cable as nearly as possible in the exact position it is to occupy after joint is made so that there will be a minimum amount of moving necessary during and after the operation of splicing.

Adjust Tag—Loosen cable tag which has been attached by the cable-pulling gang, and slide it back out of the way beyond the cable arm. If more tags are present than are necessary for the finished installation, remove the excess.

3. Prepare Lead Sleeve.—Scrape or shave the outside of the sleeve for at least 2 in. at each end, with a shaving hook, in order to give a fresh surface to insure good union of the metals in wiping the joint. Smear the freshly shaved surfaces with stearine to protect them against the formation of the usual film of lead salts which tends to prevent a good union of metals.

Slip Lead Sleeve on Cable—Slip the lead sleeve to be used over one of the cable ends and slide it back out of the way, beyond the cable arm.

4. Establish Center Line of Joint.—Choose location desired for joint, usually midway between duct faces in a manhole, and determine where center line of joint shall be. Mark by scratch on sheaths of both cable ends.

Cut Cable to Fit—In all of the 4,800-volt cable joints, butt splices will be used on the individual conductors, the conductor ends coming together at the center line of the joint. Before removing any sheath or belt insulation, saw off the cable ends square with the axis of the cable and so that the conductors will make a snug butt splice, none being too long or too short

but just fitting tightly. No cutting of conductors shall be done after sheath and belt insulation have been removed as in paragraphs 7 and 8. The joints in all conductors of a multiple-conductor cable should be opposite each other and not staggered.

5. Measure Inches from Center Line.—The distance shown on the drawings, from the center line of the joint to the end of the sheath, is the distance after the sheath is belled out. Since the bell is to be approximately ¼ in., the sheath must be cut ¼ in. longer.

Crease Sheath.—The crease should be carefully made with the chipping knife, the lead being cut only part way through.

6. Shave Cable.—The sheath for a distance of 2 or 3 in. from the crease (away from the joint) shall be scraped or shaved clean with a shaving hook in order to give a fresh surface to insure good union of the metals in wiping the joint.

Smear with stearine all the freshly shaved surfaces to protect them against the formation of the usual film of lead salts which tends to prevent a good union of the metals.

7. Remove Sheath Back to Crease.—When cutting the sheath longitudinally, great care must be taken not to cut into the insulation underneath. Insert the knife tangentially with the inside curve of the sheath. Remove the sheath by pulling apart with pliers.

Bell ends of sheath about ¼ in. using a fiber wedge for the purpose The pulling off of the sheath, if properly done, tends to form this bell. The edge of the lead should be examined carefully and all sharp edges or projections which might tend to penetrate the insulation of the cable removed by means of a knife.

8. Remove Belt Insulation.—The ends of the belt insulation should be cut off square ½ in. from the end of the sheath, as shown on the drawings, and the belt insulation removed from there to the end of the cable. Great care must be taken not to cut, scratch, or otherwise injure the conductor insulation underneath in doing this.

9. Remove Fillers.—The fillers should be cut off square as far in the crotch as possible and the fillers all removed from there to the end of the cable.

10. Phase or match conductors of the two cable ends in pairs as indicated by a phasing test. Unless matching of phases can be done without much dislocation or twisting of the conductors, phasing should not be done in that joint alone, but should be cared for in other joints. In exceptional cases it may be necessary to take care of the phasing by rearrangement of the leads at the potheads in the station or on the cable pole.

11. Remove Conductor Insulation.—This insulation should be cut off square to the copper conductor at a distance from the end of the cable or center line of the joint, shown on the drawings, and removed from there to the end of the cable, care being taken not to scratch the conductor in so doing. To prevent the paper insulation becoming loosened or unwrapped in this or succeeding operations it should be bound with twine a short distance from the end before the cut is made.

12. Fit Ends of Conductor in Copper Connector.—The connector used should be of the proper size to fit the conductor with a close sliding fit without the necessity for spreading. A split connector should close to within

3/64 in if properly fitted Wipe the ends of the conductor clean before inserting into the connector. Protect conductors against accumulation of solder by winding on 8 or 10 turns of gilling twine, starting about 1/8 in. from the end of the copper connector.

Sweat in Place—Use a small quantity of stearine for flux (no other flux permissible). Wipe the solder carefully with long pieces of cloth to remove any excess lumps or sharp edges and to thoroughly fill up the depression at the slot.

The wipe should be made so as not to leave any sharp edges or irregularities. If any such should occur however, they shall be dressed down with flint cloth, using great care not to score the conductor. Remove all dust or filings from the conductor and any exposed insulation.

13. Spread the Conductors.—This should be done with a tool made of fiber, and not of steel or other hard material The conductors should be spread no farther than absolutely necessary, as such movement is likely to disturb the insulation.

14. Apply Paper-tape Insulation.—Keep the number of rolls sufficient for one joint in a clean dry pail which has previously been held over a flame to insure its dryness In cold weather the pail should be set in a pan containing sufficient paraffine at 250°F. (by thermometer) to keep the pail warm until the compound has softened enough to permit the rolls of tape to be easily unwrapped, not until the compound is fluid. Every precaution must be taken to prevent dirt or moisture getting on the exposed rolls of tape or the conductor insulation.

Before applying tape, any cloth or twine used to protect or secure the insulation underneath shall be removed Also before applying tape over factory insulation, the outer layer of the insulation shall be removed The outer layer of insulation over which the tape is to be applied shall be drawn up tight and held with one hand while the first layer of tape is being wound on, one turn at a time This is of especial importance wherever the insulation underneath is wound in a direction opposite to that in which the taping is being applied

Tape-impregnating compound shall be spread liberally over each layer of tape before the next layer is applied The tape shall be wound tightly and smoothly with a uniform lap and without wrinkles, ridges, or depressions. Hold the tape with a small clean cloth, drawing it up tight, so that all excess compound will be forced out at the edges. Secure the ends of the tape in the final layer by tying tightly with twine.

15. Separators.—A 1/8 in belt of impregnated paper tape should be wound around each of the conductors to hold them apart and allow the joint filling compound to flow freely between them when filling the joint.

16. Tie conductors together with gilling twine, wrapping 3 or 4 turns around all three conductors at center of joint over 1/8 in belt separators.

17. Belt insulation shall be applied as indicated on the detailed instructions for each joint, to protect the cable insulation at the sheath bell and hold the conductors together at the crotch. This shall be applied in accordance with the rules for paper-tape insulation given in paragraph 14.

18. Tape-impregnating compound heated to 250°F. (measured by thermometer) should be poured over the insulation after the hand-applied

insulation is finished so that the joint is thoroughly boiled out and saturated with it.

19. Fit Lead Sleeve in Place.—Slide it back over joint, being careful that it is centered as nearly as possible. To aid in this the sheath should be marked 2 in. back from each sheath bell.

Beat down ends as closely as possible around the cable sheath, being careful not to injure sheath or disturb the splice. Be sure the sleeve is concentric with the cable when finished.

Wipe on to Cable Sheath.—Use paper paster to protect sheath and sleeve beyond the wipe. Be sure that the ends of the sleeve are completely sealed and joined to the cable sheaths and that the completed job is smooth and solid.

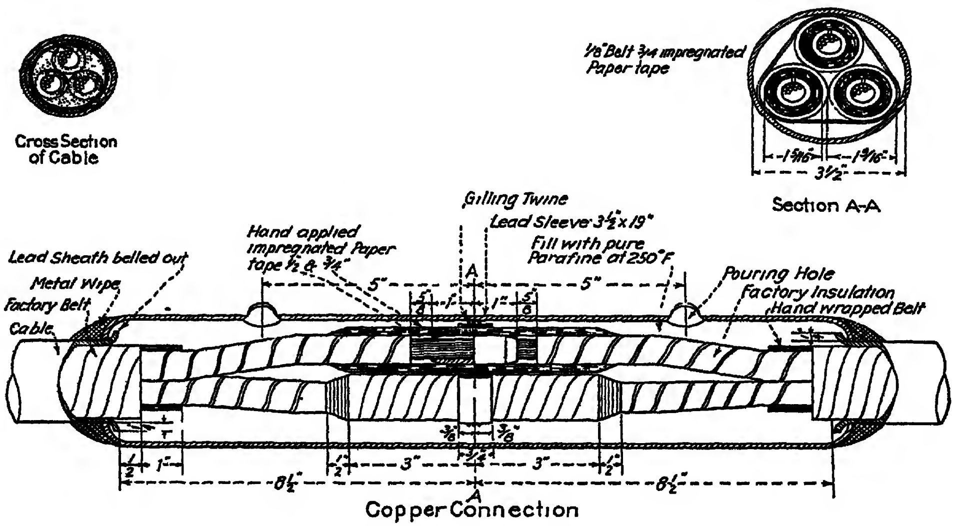


FIG 293.—Typical 4,800-volt cable joint.

20. Pouring holes are provided in the lead sleeve for all 4,800-volt joints, one near each end.

21. Fill Joint with Paraffine.—Use pure paraffine. Be sure the paraffine is as nearly as possible at 250°F. (measured by thermometer). Tilt the whole joint so that one hole is about ¼ in. above the other. Pour the paraffine into the lower hole. Pouring shall be continued until the paraffine comes out of the upper hole freely and clear, without bubbles. Excess paraffine may be caught in a clean dry pail and used again, if heated.

Allow joint to cool at least 1 hr, restore to a horizontal position, and refill with pure paraffine at 250°F. It is important that a perfect filling be secured before closing pouring holes.

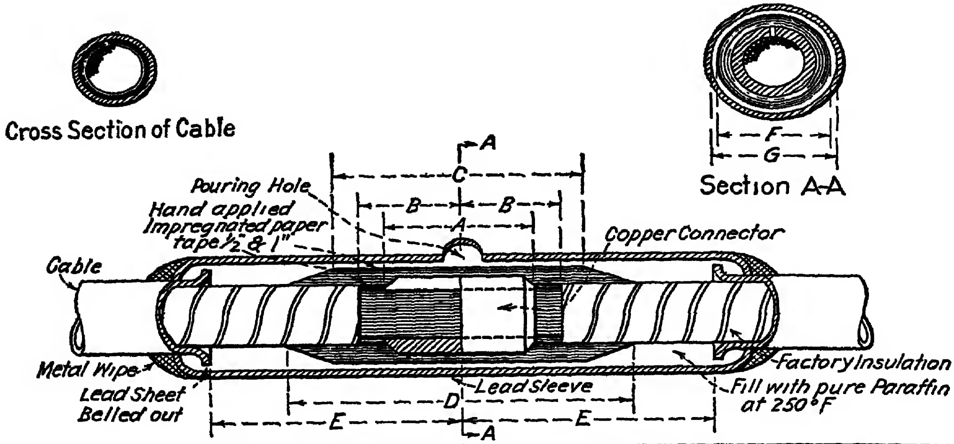
22. Close Pouring Holes.—The two openings should be closed by gently folding down the lead flaps, the edges of which should be lightly peened down to exclude any drops of solder from penetrating the interior. The cuts should then be carefully sealed with the soldering iron.

Figure 293 gives a cross-section of a typical joint from the same specifications. The instructions given in connection with it show the order in which the operations in making the joint shall be carried out The numbers given with each operation refer to the corresponding paragraph in the preceding general instructions, in which each operation is described in more detail.

Operations in Making

4,800 Volt, 200M. c m , Three Round Conductor Cable Joint

a. Train cable Adjust tag (paragraph 2)
b Prepare lead sleeve Slip lead sleeve on cable (paragraph 3)
c Establish center line of joint Cut cable to fit (paragraph 4)
d. Measure 8¼ in away from center line on each cable end Crease sheaths (paragraph 5)
e. Shave cable near crease Smear shaved surfaces with stearine (paragraph 6)
f. Remove sheath back to crease Bell ends of sheath ¼ in (paragraph 7)
g Remove belt insulation to ½ in from end of belled-out sheath. Cut off ends of insulation square (paragraph 8)
h. Cut off fillers square as closely in crotch as possible (paragraph 9)
i Phase and match conductors (paragraph 10)
j. Bind conductor insulation on each conductor with cord about 2½ in from end to prevent unwrapping (paragraph 11)
k Remove conductor insulation on each conductor for a distance of 1⅝ in from the end, cutting off ends of insulation square (paragraph 11)
l Wipe ends of conductors clean and fit into copper connectors Protect conductor against accumulation of solder by winding on 8 or 10 turns of gilling twine, starting about ⅛ in from the end of the copper connector Sweat conductors into connectors Dress down rough surfaces and wipe clean (paragraph 12)
m Spread conductors (paragraph 13)
n. Remove gilling twine from one conductor Wipe the copper connector and conductor thoroughly with a strip of dry cloth (paragraph 14)
o Apply ½ in paper-tape insulation over the conductor and copper connector building up flush with factory insulation (paragraph 14)
p Remove binding cords around insulation. Remove outer layer of factory insulation back to belt insulation (paragraph 14)
q Apply ¾ in paper-tape insulation Build up to size and contour shown on drawing, *i e*, 1⁵⁄₁₆ in in diameter for 3 in each way from center line, then tapered down to the factory insulation for a distance of ½ in at each end, total length 7 in (paragraph 14)
r Repeat operations *n* to *q* inclusive for other two conductors
s Apply ¾ in paper tape around each conductor, at the center, building up a belt ⅛ in thick to act as separators (paragraph 15).
t Bind all conductors tightly together with gilling twine wrapping three or four turns around center of joint (paragraph 16).
u Apply ¾ in papertape insulation around all three conductors next to factory belt insulation for a distance of 1 in. Build up flush with factory belt Total length of finished belt shall be not over 1½ in from end of sheath bell (paragraph 17)
v. Pour hot tape-impregnating compound (250°F by thermometer) over whole joint, thoroughly boiling it out and saturating it (paragraph 18)
w Fit lead sleeve in place, beat down ends and wipe to cable sheath (paragraph 19).
x Fill joint with hot pure paraffine (250°F by thermometer). Allow to cool 1 hr or more, fill again, and allow to cool ½ hr Fill again and repeat as many times as necessary to completely fill joint (paragraph 21)
y Close pouring holes by bending down lead flaps, peening lightly and soldering tightly (paragraph 22)
z Attach bonding connections.
aa Apply fireproofing.
bb. Fasten tag securely in proper location.

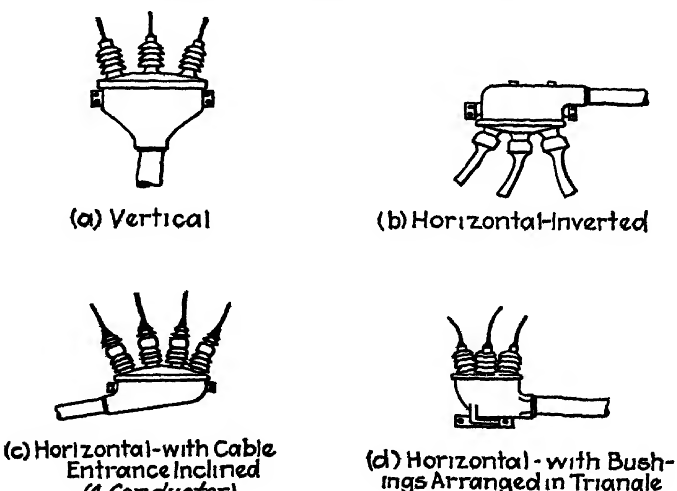


SIZE	A	B	C	D	E	F	G	LENGTH OF SLEEVE	SIZE	A	B	C	D	E	F	G	LENGTH OF SLEEVE
1000 MCM	3"	2"	5"	7"	5"	2¼"	2½"	12"	350 MCM	2½"	1¾"	5"	7"	4"	1½"	2"	10"
750 MCM	2½"	1¾"	5"	7"	5"	1¾"	2¼"	12"	200 MCM	2"	1½"	5"	7"	4"	1½"	2"	10'
500 MCM	2½"	1¾"	5"	7"	4"	1⅝"	2"	10"									

Fig. 294 —Typical 600–volt cable joint.

Figure 294 shows a low-voltage cable joint.

Potheads.—Where underground cables come up and are attached to the overhead, the ends of the cables must be sealed



(a) Vertical

(b) Horizontal-Inverted

(c) Horizontal-with Cable Entrance Inclined (4 Conductor)

(d) Horizontal - with Bushings Arranged in Triangle

Fig. 295.—Types of potheads.

against the entrance of moisture. With some types of nonmetallic sheathed, rubber-insulated cables this sealing may be

done with tape and compound but for most cases with lead-sheathed cable and paper insulation some form of pothead is

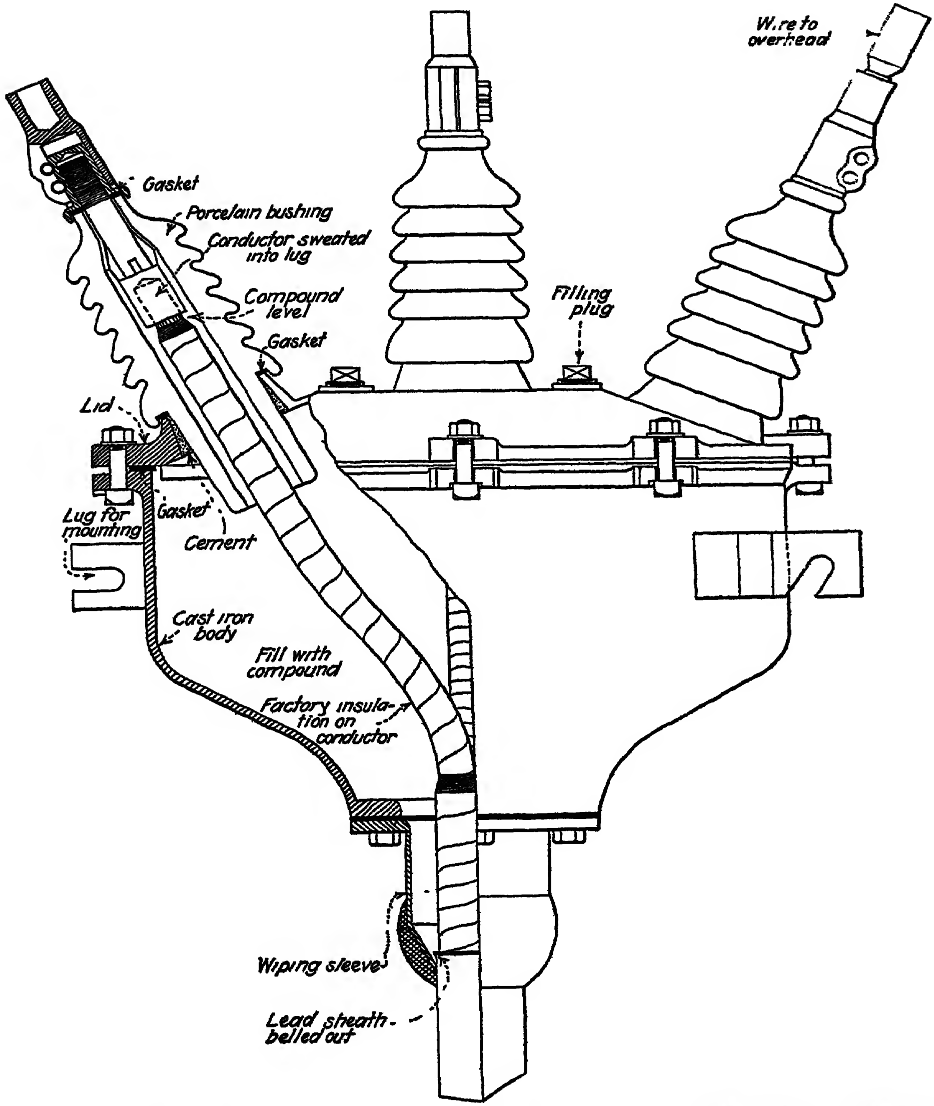


FIG 296.—Makeup of one type of vertical pothead for 4,800 volt or 6,600 volt service (*G. & W. Electric Specialty Co.*).

necessary to make this seal. The pothead usually consists of a cast-iron tank or pot into which the cable is inserted, the sheath

being wiped or clamped at the entrance The conductors pass through the pot and are either brought out through porcelain

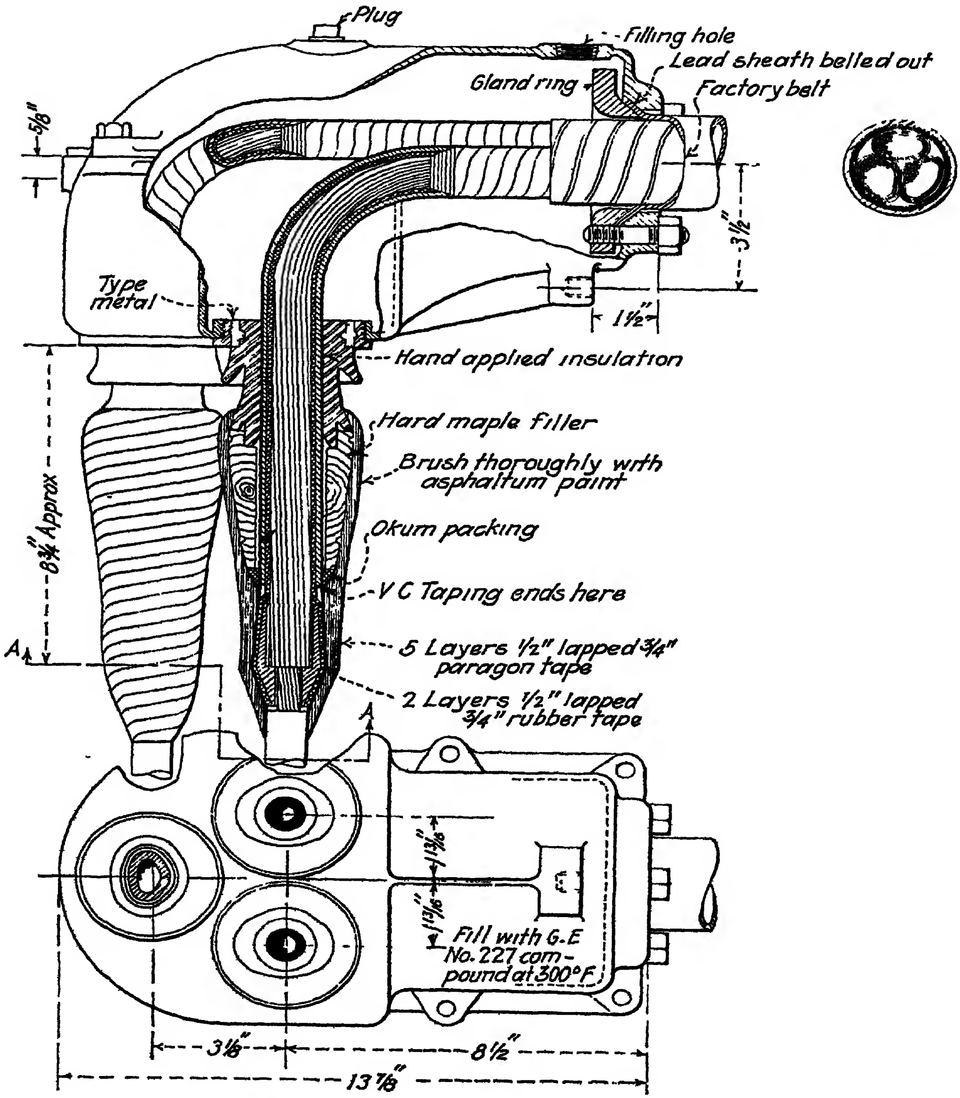


Fig. 297.—Makeup of one type of inverted pothead for 4,800 volt service.

bushings, or are attached to conducting terminals fixed in the bushings .The pot is then filled with insulating compound. In

choosing and installing a pothead the main objects for using it should be kept in mind, i e ,

1 Sealing the cable end from the entrance of moisture

2. Insulating the conductor effectively from the metal sheath where the two separate.

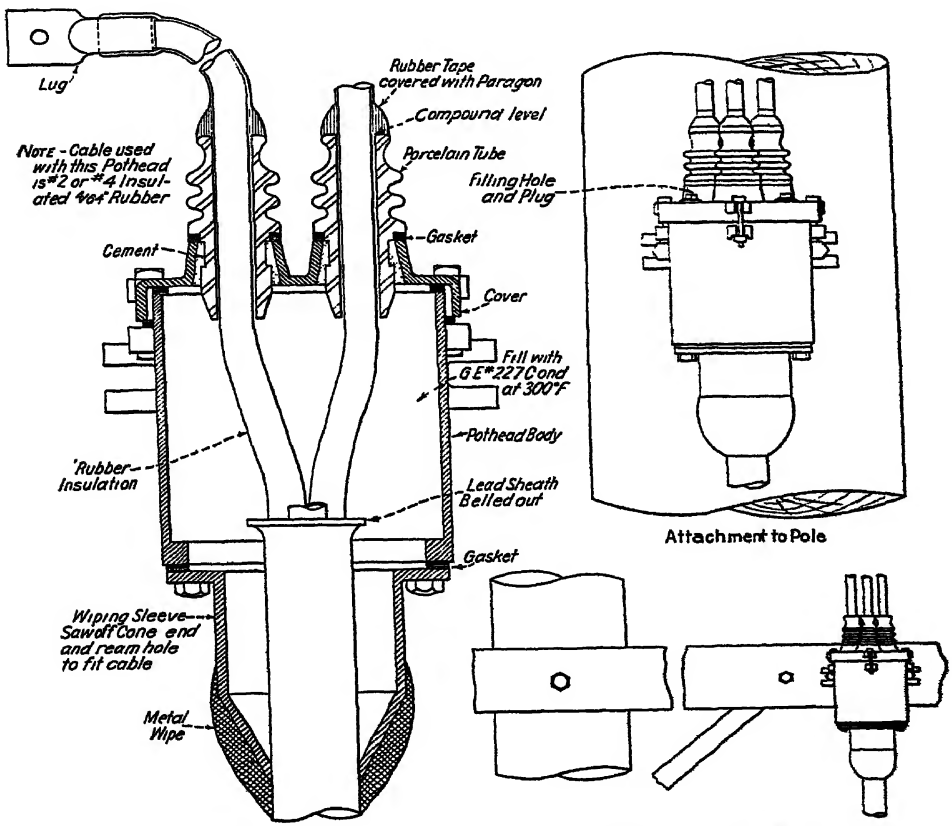


Fig 298 —Makeup of one type of 600-volt pothead (G & W Electric Specialty Co).

Potheads are in general of two types, which may be distinguished as vertical, *i.e.*, with the open-wire conductors issuing from the top, and inverted, with the open-wire conductors issuing from the bottom, see Fig. 295 The vertical pothead may have the cable entering directly at the bottom, at an angle, or horizontal as shown in Fig. 295.

In making up a pothead the same precautions should be used as in making up a cable. These were indicated above under "Cable Joints."

Figure 296 illustrates the make-up of a vertical pothead for primary voltages.

Figure 297 shows an inverted type with the conductors passing directly through the bushings

Figure 298 is the make-up of a low-voltage pothead for secondary voltages.

CHAPTER XXVII

TYPICAL CONSTRUCTION

In the following pages will be shown a number of photographs illustrating typical examples of some of the features of construction discussed in the other chapters These are offered, not as the only possible types of construction, and perhaps not the best possible types in all cases, but rather as what may be considered typical good construction. It has been, in general, designed on the basis of the principles here set forth. For this reason all of the examples are taken from one system rather than attempting to obtain them from different systems in different parts of the country. It is believed that good construction will not be widely different no matter where it is found and hence examples from one locality are as satisfactory for general purposes of illustration as those taken at random.

With each picture will be given a brief discussion of the main features which it is intended to illustrate.

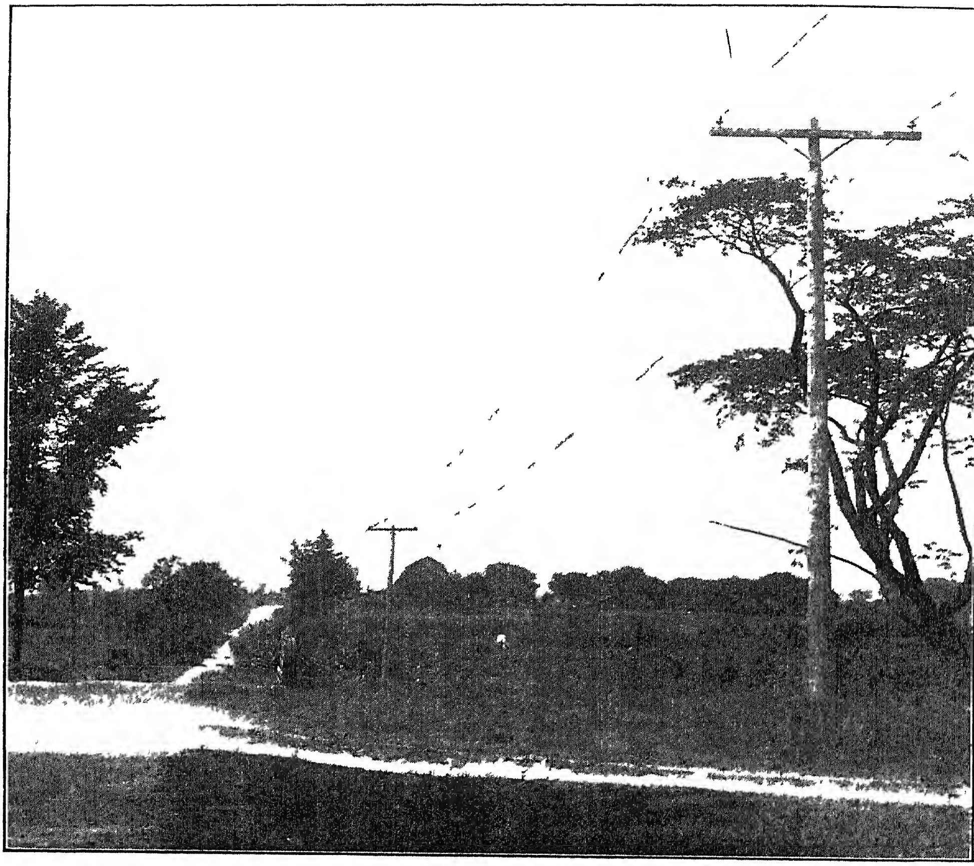


FIG 299 —Rural or farm line, single-phase

This line is constructed with 35-ft Northern White cedar poles, spaced 300 ft. apart. Crossarms are 96-in, Douglas fir The conductor is No 2 bare A.C S R. In the foreground, the line occupies the side of the highway, but, in the distance where trees are encountered, it is offset to private property to avoid using higher poles or trimming the trees. The voltage is 4,800 volts.

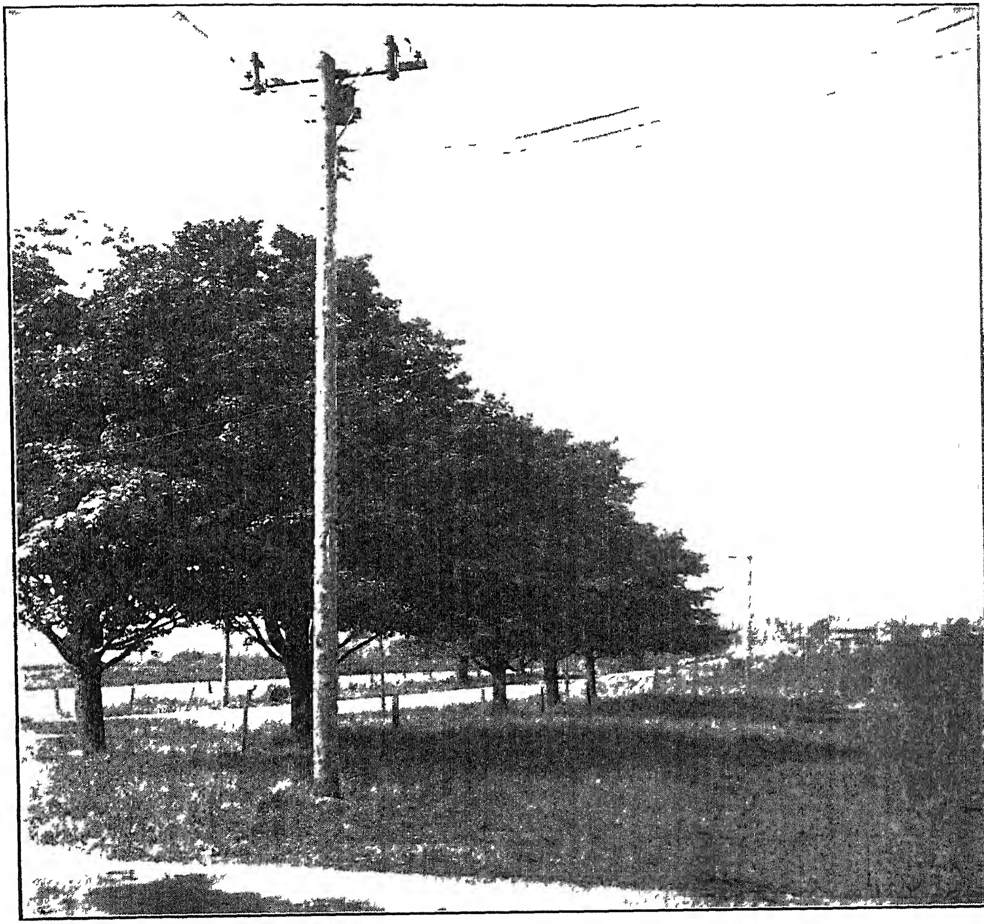


FIG 300—Rural line behind trees

This line is similar to that in Fig 299, the location behind the trees being more clearly evident. A typical transformer and service installation is shown in the foreground. A close-up picture of such a transformer is shown in Fig 314

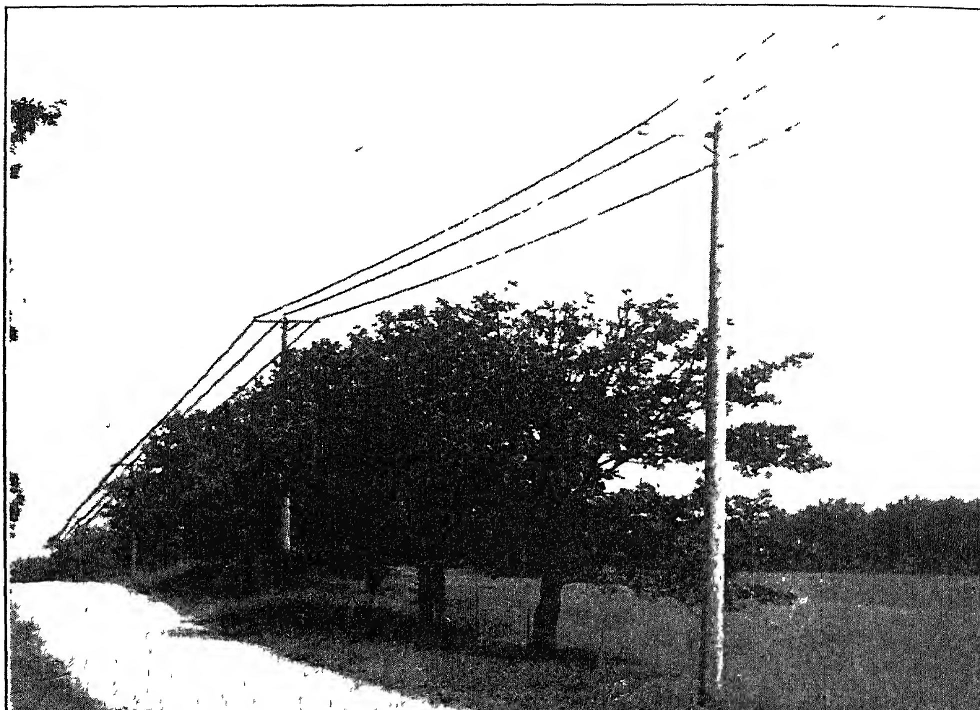


FIG 301.—Three-phase rural line over trees.

This line is of similar character to that shown in Fig 299 and 300 except that the third-phase conductor is added, carried on a ridge top bracket In this case, clearance over trees is gained by use of higher poles and symmetrical trimming of the trees

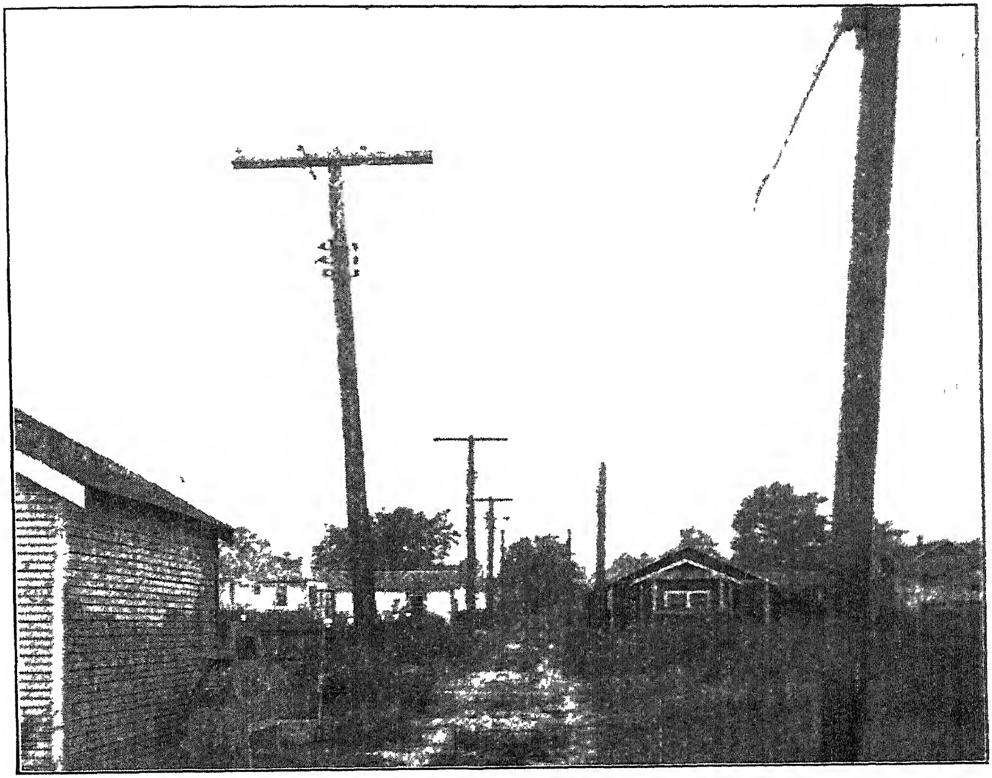


FIG. 302 —Light distribution line—secondary on racks

The primary is three-phase, 4,800-volts, spaced 28 in apart The secondary is carried on secondary racks A transformer installation may be seen in the distance A close-up of such an installation is shown in Fig 315 The pole in the foreground is fitted up to carry some dead-end stress, it being adjacent to a corner pole Double crossarms are used, one end of the arm is held with an arm guy, and the pole, itself, is guyed to a guy anchor The line occupies one side of an alley, the other side being used by a telephone distribution line as may be seen

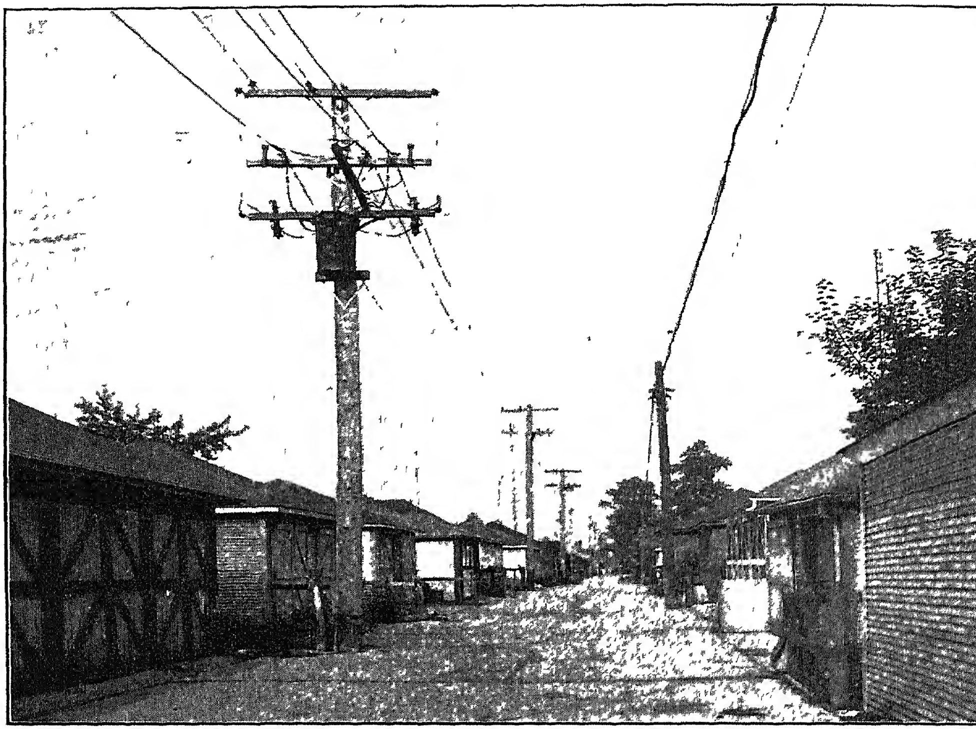


FIG 303 —Light distribution line—secondary on crossarms

This line occurs in a well built-up city district The poles are 40 ft Western Red cedar, spaced about 120 ft apart The primary is 4,800-volt, single-phase, with 28 in between conductors The secondary is carried on crossarms placed 4 ft below the primary arm, allowing space for an intermediate arm if such ever becomes necessary to accommodate additional circuits The transformer installation in the foreground is shown in closer view in Fig. 316.

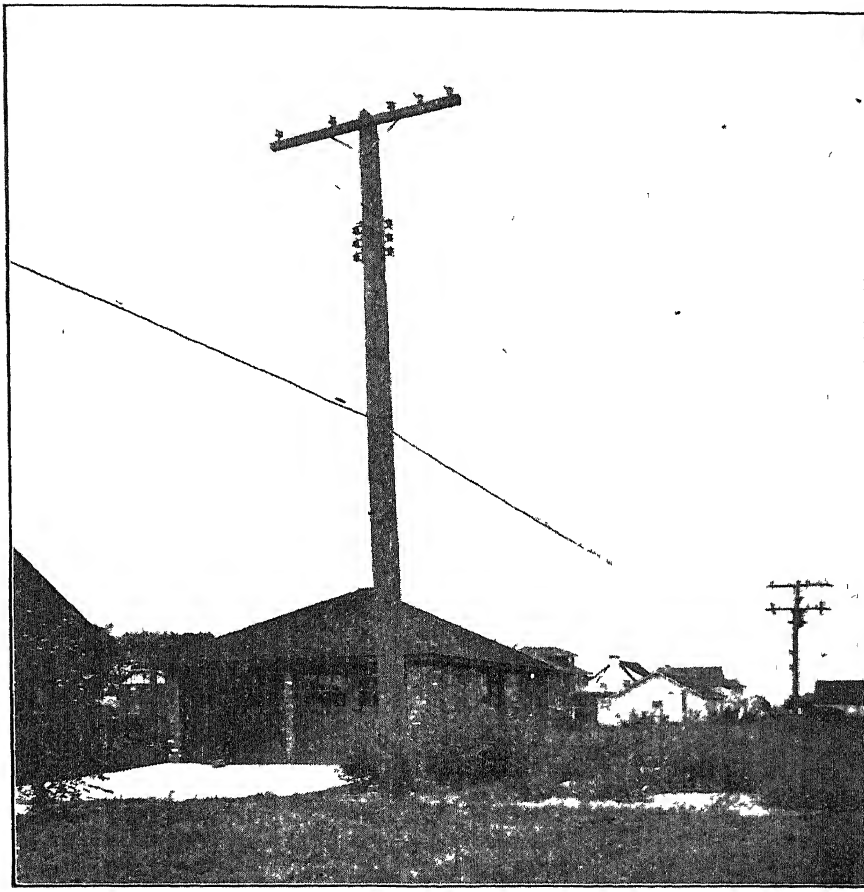


FIG. 304 —Joint construction with telephone circuits

The improved appearance of right-of-way, due to the elimination of one of the lines of poles, is apparent, when this is compared to the lines shown in Fig 302 and 303 On the second pole, the transformer pole, the guard arm over the telephone cable may be seen, the spacing on this pole being such as to require it On the first pole, the telephone cable is more than 6 ft below the secondaries and hence no guard arm is necessary The primary arm in this case carries a three-phase primary circuit and a street-lighting circuit (on glass insulators on the right-hand end of the arm).

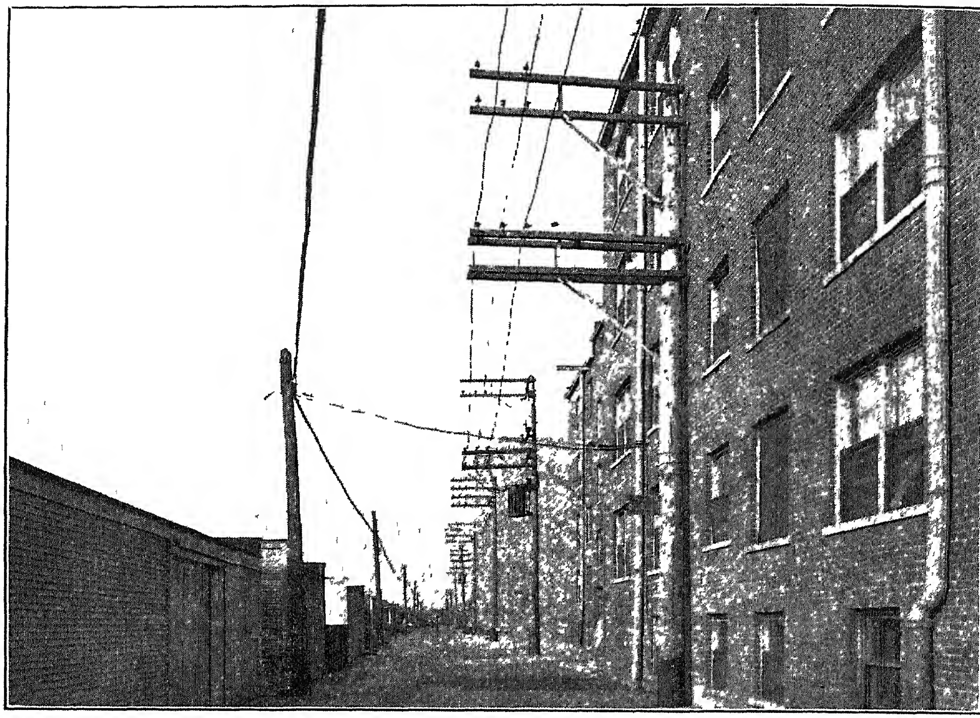


FIG 305 —Side-arm construction.

The wires are carried well away from the building in order to provide ladder space next to the building for the raising of fire ladders Arms 120 in long are used, with 7-ft, side-arm braces Reversion to ordinary crossarm construction may be seen in the distance The upper arms carry a three-phase primary circuit (in triangular arrangement) and a street-lighting circuit The lower arms are for secondary The wide spacing between groups of arms in this case came about from a consideration of the relative levels of the wires and the windows in the building On the first pole the use of two sidearm braces with one arm is illustrated on the upper arms The lower arms are doubled and arm guyed, being adjacent to a dead end The transformer installation on the second pole should be noted.

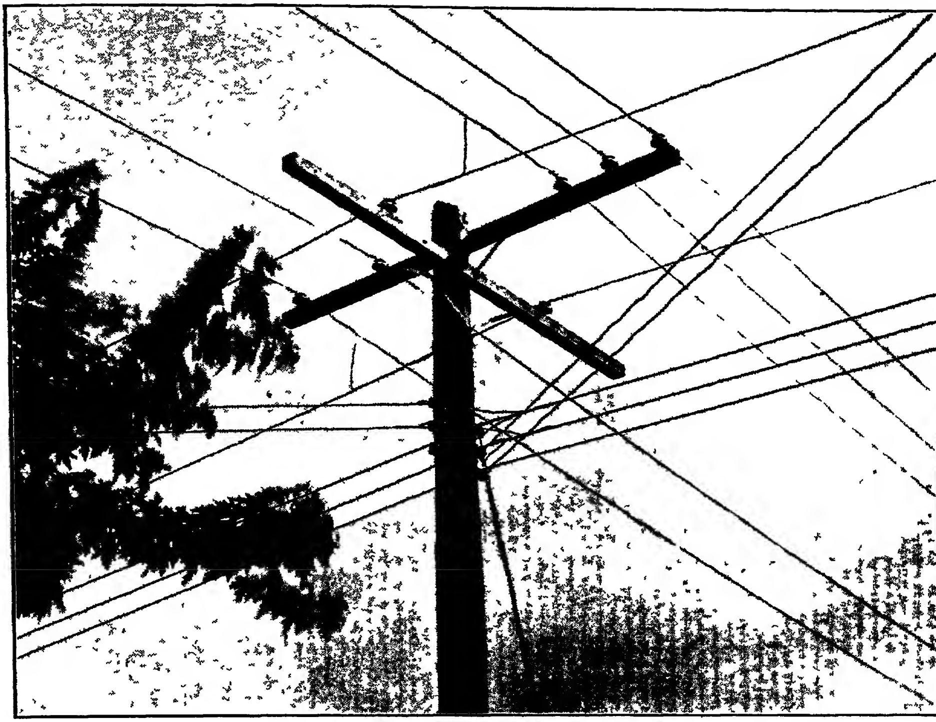


FIG 306 —Corner pole—light construction.

This is an intersection pole, no wires being dead ended on it. In order to provide a 30-in climbing space, 120-in crossarms were used, the climbing space occuring on the "corner" of the pole on the left-hand side of the picture. Between the back of each crossarm and the adjacent wire on the opposite side of the pole 30 in. is provided. The circuits shown are a three-phase primary circuit and a street-lighting circuit running in one direction and a single-phase tap off the three-phase circuit in the other direction. Some details of secondary rack construction are indicated. The method of tapping off services from the line rack on one side of the pole and from an auxiliary rack on the other side of the pole is clearly shown.

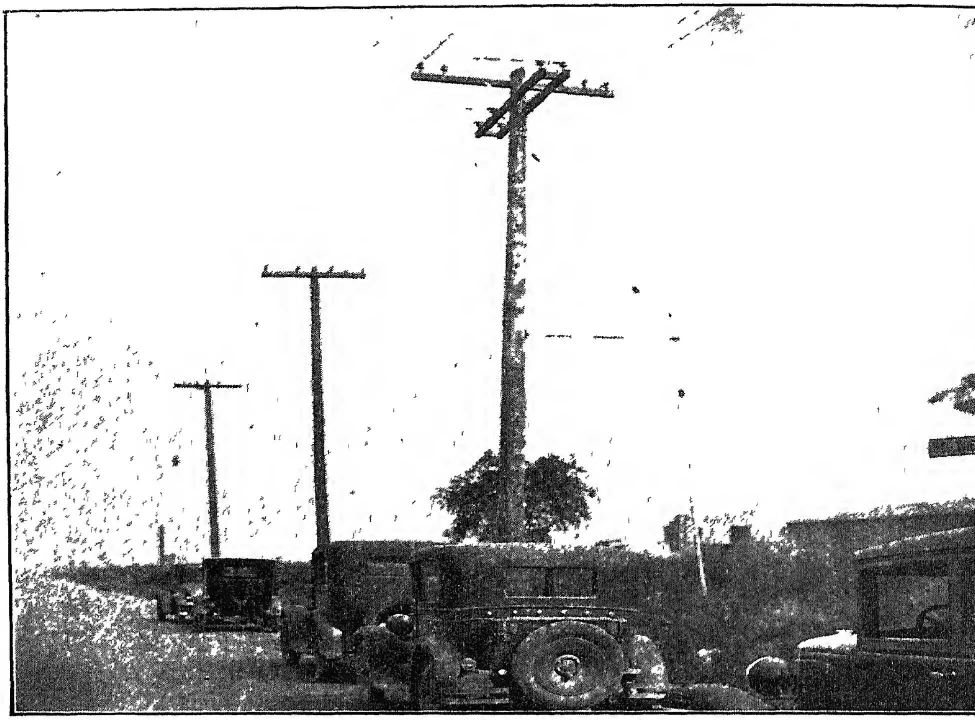


FIG 307 —Corner pole-light construction.

The three-phase tap is dead ended on the corner pole in this case and double arms are used to hold the stress. The pole is guyed against this stress by a vertical or sidewalk guy The guy protector on the lower end of this guy should be noted This is used largely to increase the visibility of the guy The normal arrangement of the line may be seen on the second pole where the three-phase circuit dead ends. On the corner pole, the spacing is somewhat altered in order to provide climbing space past the double arms The street-lighting circuit continues on to the third pole where it is brought to the two pole pins and dead ended, the stress thus being balanced. An arm guy and a pole-to-pole guy are used on the second pole The third pole is guyed (across a street) to a guy stub A bracket type of street-lamp fixture may also be seen on this pole

FIG. 308.—Corner—heavy construction.

In order to provide better clearances and climbing space on the corner pole and to facilitate holding the stress, all wires are carried past the corner pole one span. The corner pole thus becomes an intersection pole only and no double arms are necessary. It may be seen that longer arms (120 in.) are used on this pole to give climbing space. Guys are distributed over several poles along the lead rather than placing them all on one pole.

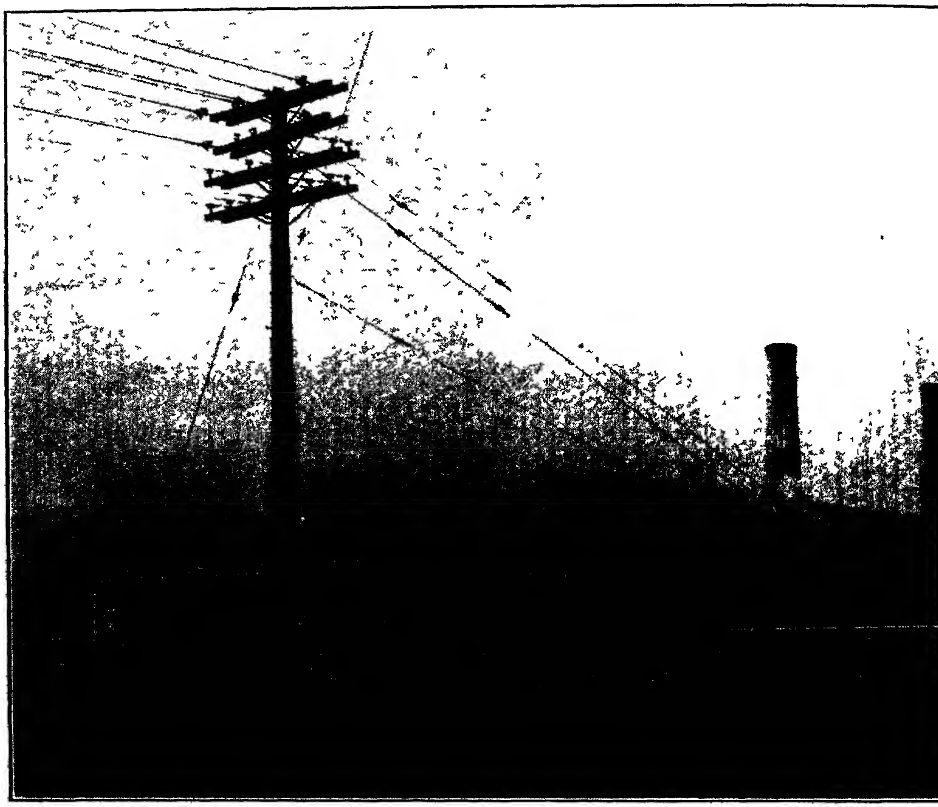


FIG. 309.—Heavy dead end.

Attention is called to the method of dead ending the heavier wires in strain insulators and the lighter wires on two pin-insulators. The heavy guying from pole to stub and from stub to anchors is an important feature. The use of strain insulators in the guys and of guy protectors is to be noted. The pole is also side guyed both ways, it being part of a railroad crossing.

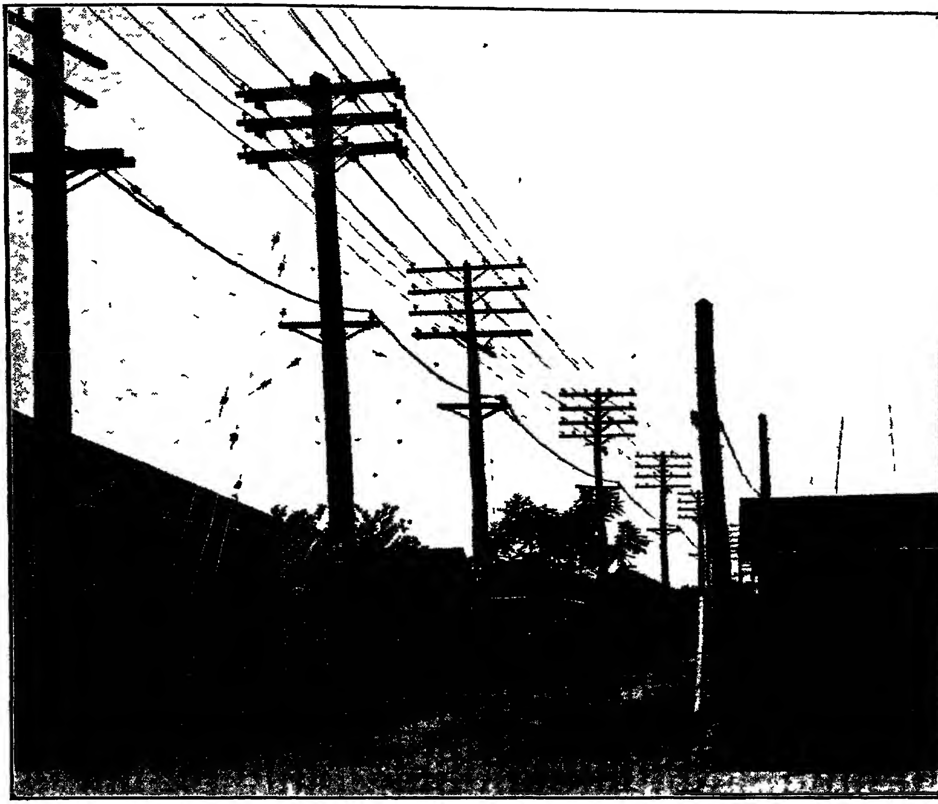
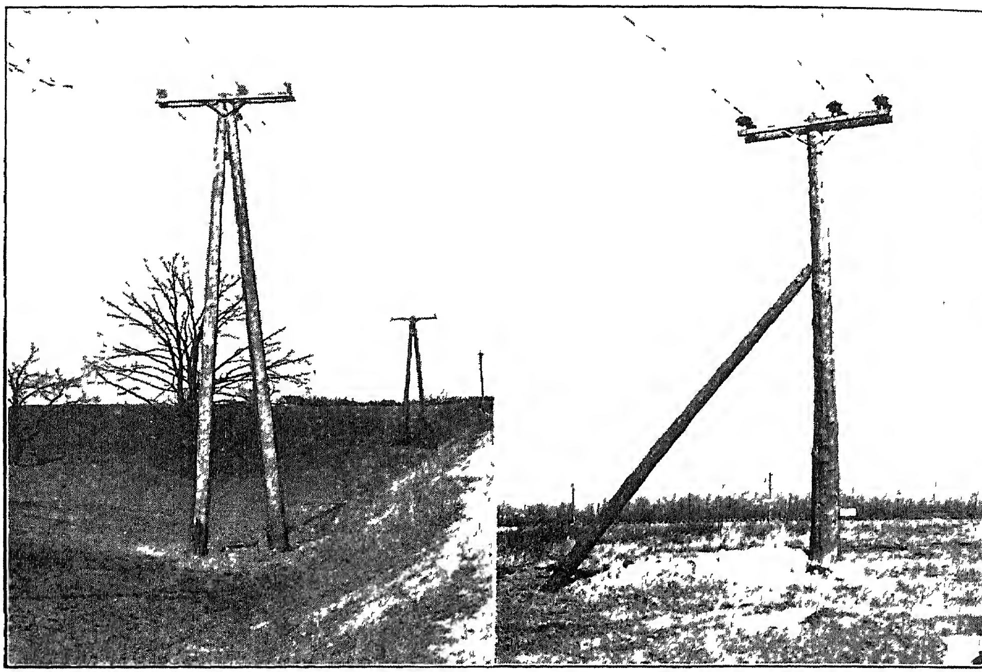


Fig. 310.—Heavy lead.

This lead is heavily loaded, most of the wires shown being No. 0000. The method of bracing the crossarms will be noticed. This is shown in a larger scale in Fig. 312. The poles in the picture are adjacent to a dead-end pole which is so located that it cannot be well guyed. Hence, the stress is carried by a distribution of guys over several poles, as shown. The use of guy insulators and of shims and guy hooks where the guys are attached to poles are points to be noted.



(a) (b)

FIG 311 —A frame and push guy.

A comparatively simple type of A-frame construction is illustrated in (a) and a pole brace or push-guy in (b). Details of both these are given in Fig. 260. The lines supported happen to be in both cases 24,000-volt circuits.

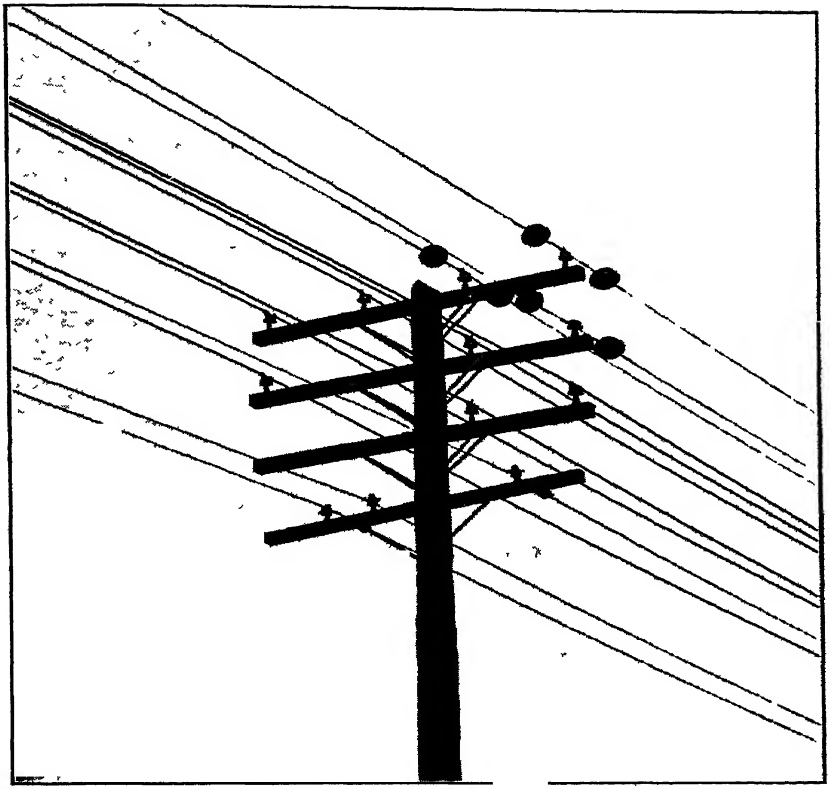


FIG. 312.—Cutting primary circuit.

A 4,800-volt primary circuit has been cut into two sections by the insertion of two Hewlett disc insulators served into each conductor. Attention is also called to the method of bracing the crossarms. Four 28-in. flat steel braces are used with each arm, two on the face, and two on the back, with three lags fastening the braces to the pole. This gives a rigid structure for unbalanced loads. It is also shown in Fig. 196.

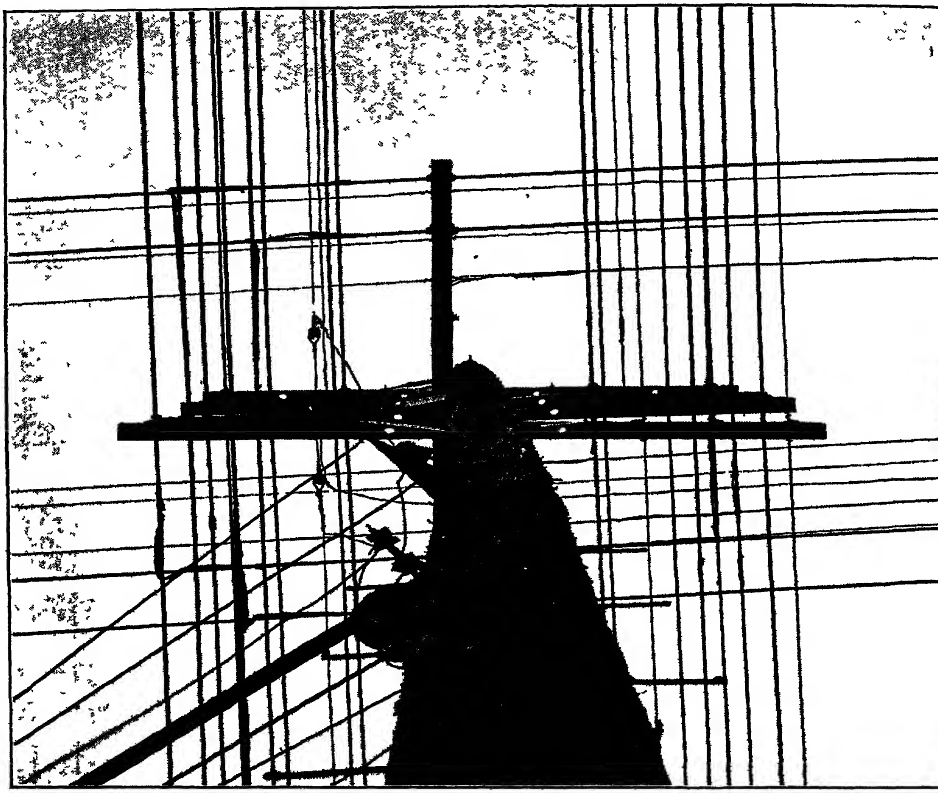


FIG 313.—Climbing space.

This shows how a 30-in. clear climbing space up the pole may be provided on an intersection pole, even with a heavy lead, by the use of 120-in. crossarms, The advantage, from the standpoint of the lineman, who has to climb the pole. over the congested pole construction sometimes seen is evident.

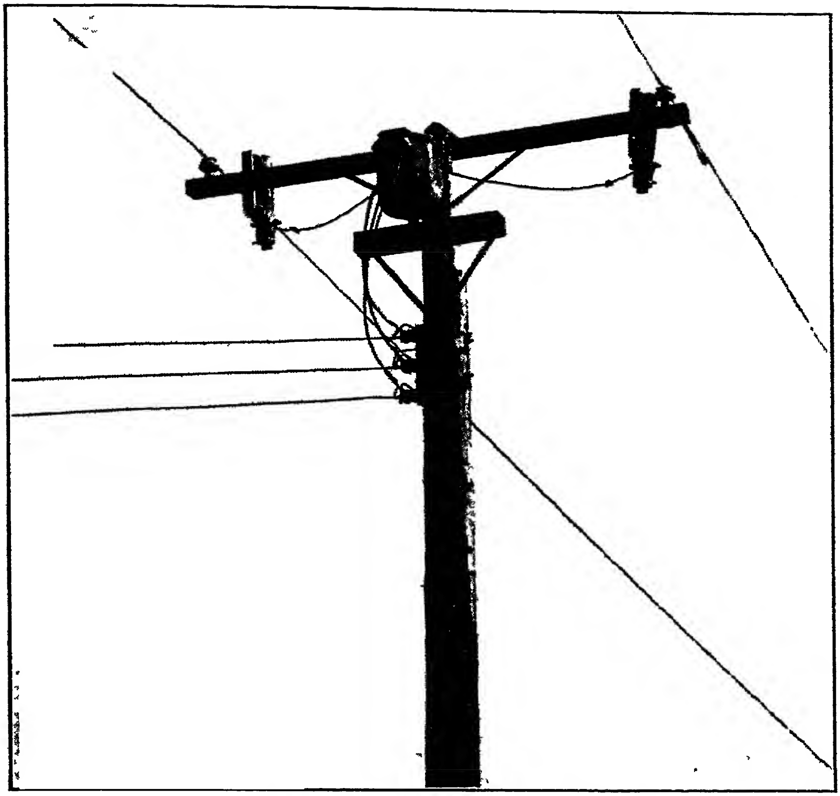


FIG. 314.—Single-phase transformer installation—rural.

This is the installation used with the lines shown in Fig 299 and 300. The transformer is 5 k-va. The primary fuses are an enclosed cartridge type mounted in a housing made of fiber similar to fiber conduit No lightning arresters are used with the installation shown, although they could be added without difficulty In most cases, a separate transformer is installed for each customer, the service being taken directly off the secondary rack shown on the pole.

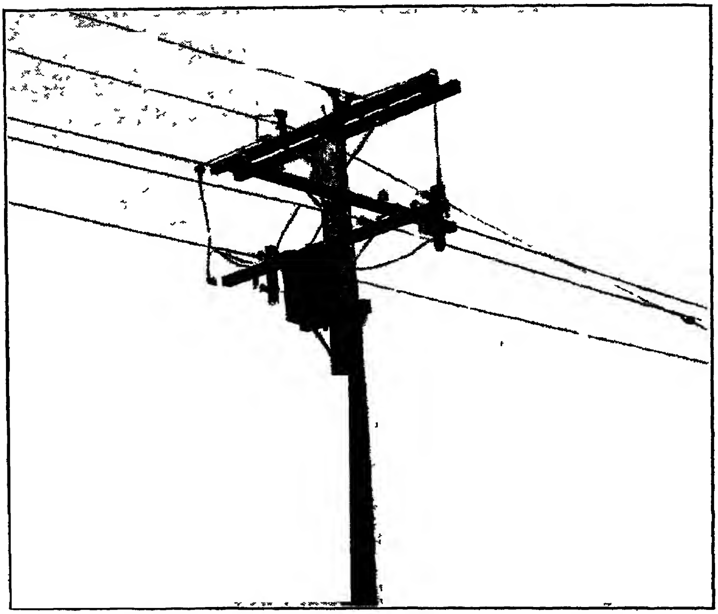


FIG. 315.—Single-phase transformer installation.

This installation is similar to that shown on Fig. 302 although it may just as well be used where the secondary is carried on crossarms throughout. With secondary rack construction, in order to conserve space on the transformer pole and to provide better clearances, the secondary is carried on the crossarm which supports the transformer. The primary fuses are also carried on that arm A buck arm is placed immediately above the secondaries for the purpose of taking off services Lightning arresters are used, carried on the same crossarm with the primary wires. In this case, a third arrester is placed in the connection from the two arresters to ground. Primary trainer wires are carried on corner brackets attached to the ends of the crossarms.

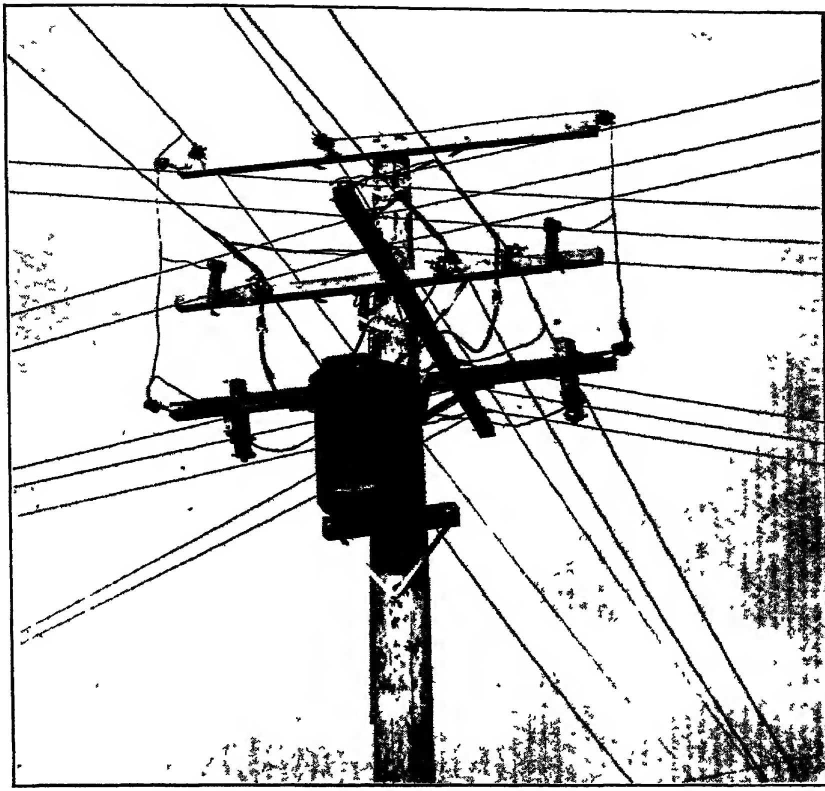


FIG. 316.—Single-phase transformer installation.

This installation is used in locations where it is desirable to keep the primary arm as clear as possible The transformer is moved down to a third arm below the secondary arm. The lightning arresters are moved down to the secondary arm. Otherwise the installation is similar to that shown in Fig. 315. It is also shown in the line in Fig. 303. Secondary fuses may be seen installed in the secondary trainer wires just below where they are tapped to the secondary mains The use of wood moulding covering the ground connection from the arresters is also shown.

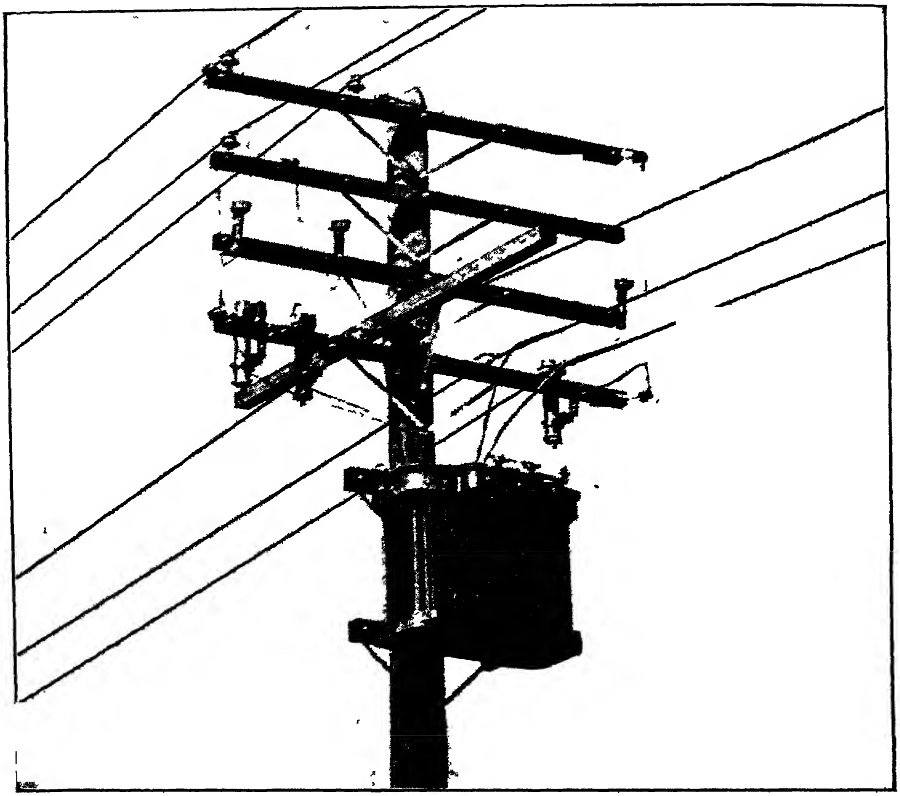


Fig. 317.—Three-phase transformer installation.

The primary fuses in this case are carried on the same arm with the secondary. Since the primary leads enter the transformer case at the front, in order to provide clearance over the cover the transformer is mounted 3 ft. below this arm. It is carried on 4 by 6 in. short arms. The arresters are shown on a separate arm. Other wires, such as single-phase secondaries, may also be carried on this arm if required. A buck arm for future services off this pole is included.

FIG. 318.—Transformer platform—three-phase transformer.

The platform is similar to that shown in Fig. 269, being constructed with simple wooden beams and side-arm braces. The primary bus is on the left-hand side of the pole, the secondary bus on the right-hand side, both being carried on pin-type insulators. The transformer is a 100-k-va., three-phase transformer, with space on the platform for two additional transformers.

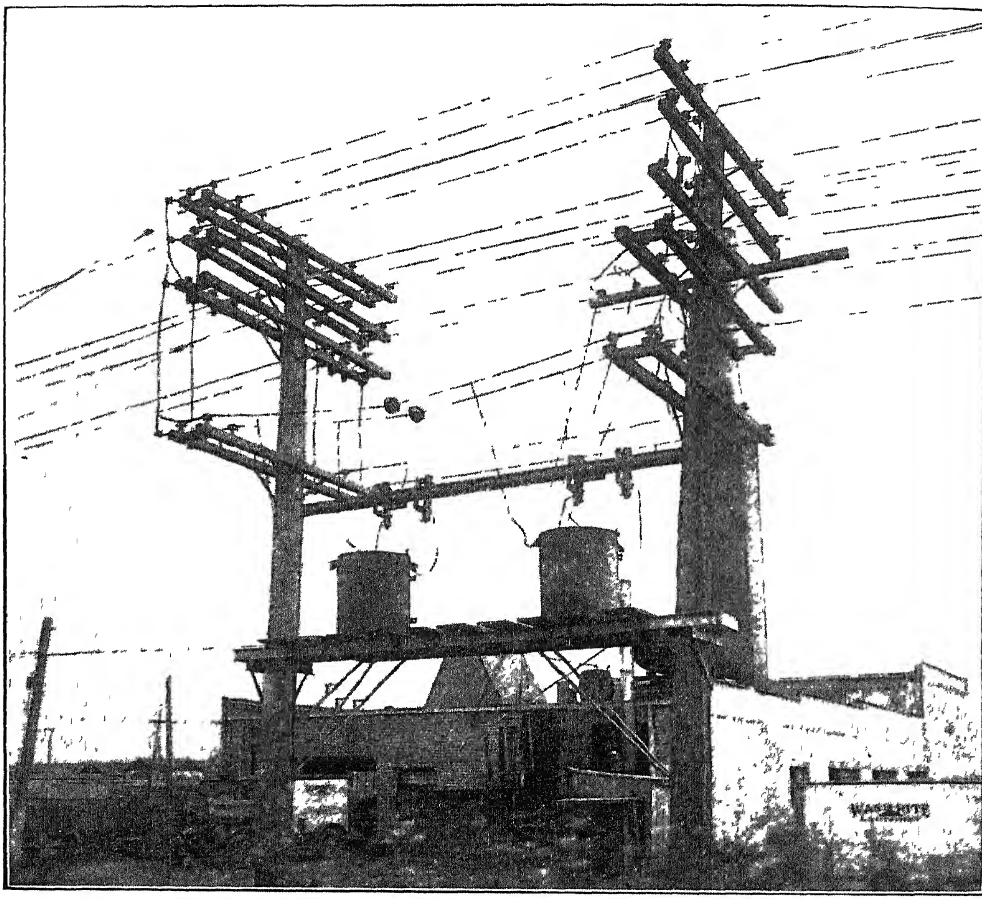


FIG 319 —Transformer platform—series street-lighting transformer

This platform is constructed with steel channels and side-arm braces Details of the design are shown on Fig 271 The brace seen to the extreme left carries an extension of the flooring of the platform on the side away from the picture, which furnishes access to the front of the transformers and the fuses. The primary fuses are supported on a beam above the transformers.

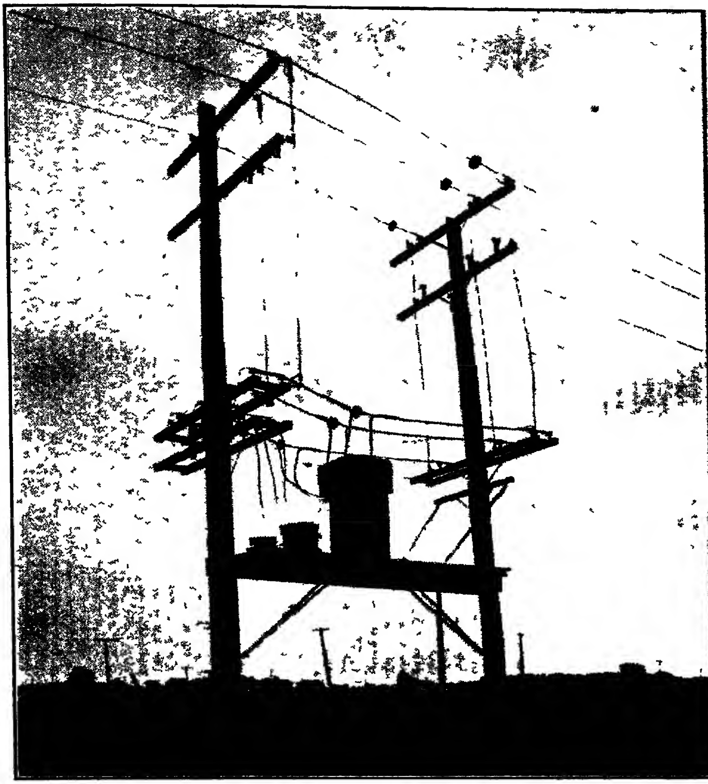


FIG. 320.—Transformer platform—induction regulator.

The platform construction is similar to that in Fig 318. The three-phase transformer serving the regulator motor and the small single-phase transformer supplying potential to the control are seen on the platform with the regulator. A simple hand-rail made with two side-arm braces is shown to the right. The method of separating the regulated from the unregulated side of the circuit both on the bus and on the pole top by cutting in strain insulators is evident The regulated side is to the left.

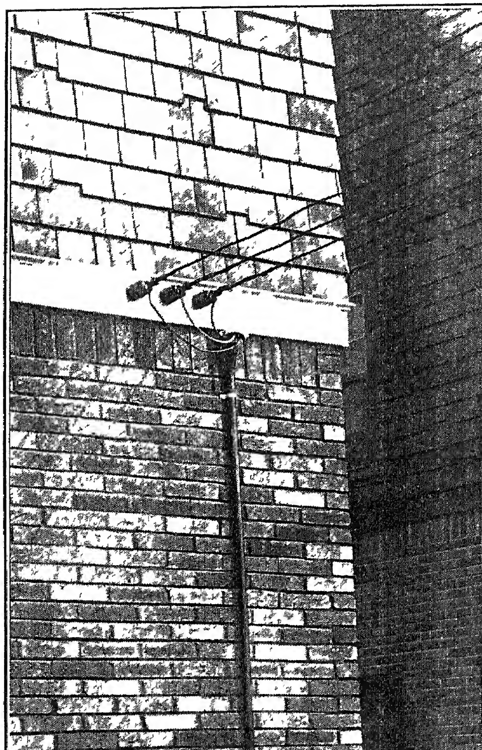


FIG 321*a*—Light service wiring—single-phase

The service brackets used are single-point porcelain brackets or insulators with integral screw These are shown on Fig 221

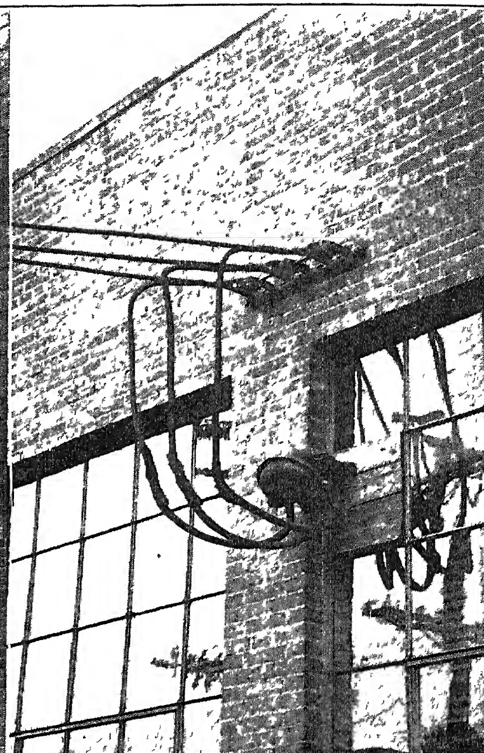


FIG 321*b*—Heavy service wiring—three-phase.

The use of a secondary rack for such heavy wiring is shown The rack is attached to the wall with expansion bolts

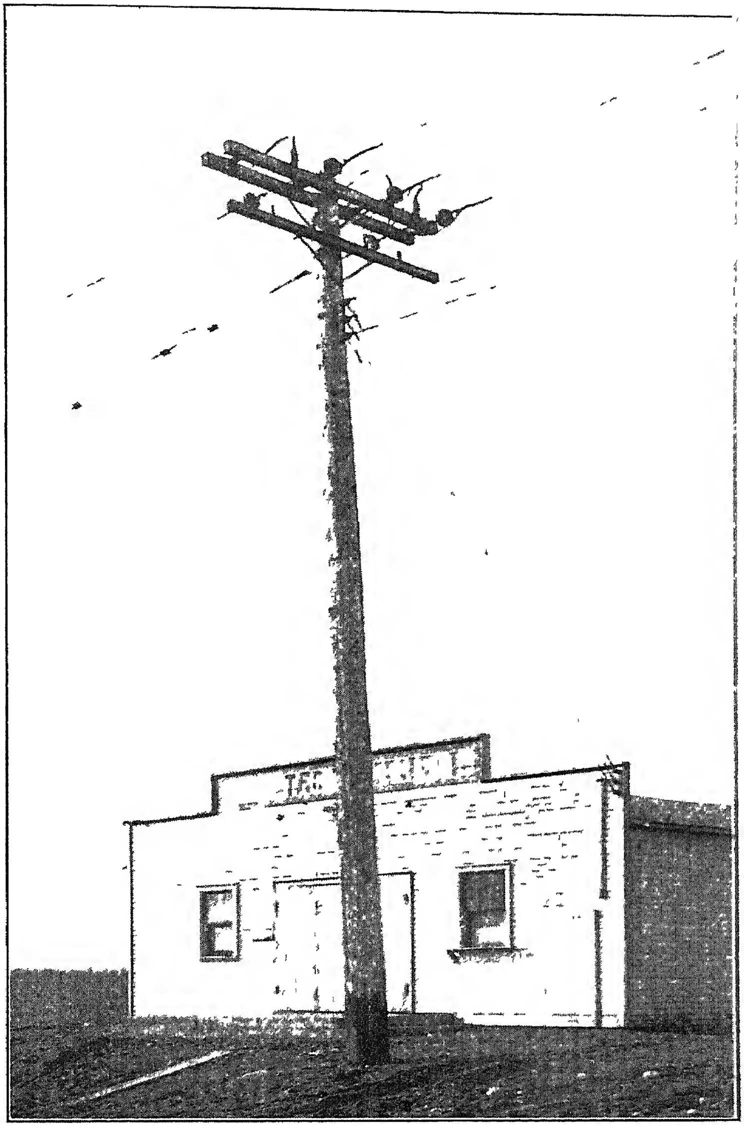


Fig 322 —Disconnecting potheads.

This is a jumpering point between two sections of a circuit The use of strain insulators for dead ending the circuit on both sides of the arms may be noted The lower crossarm is not an essential part of the disconnecting pothead installation

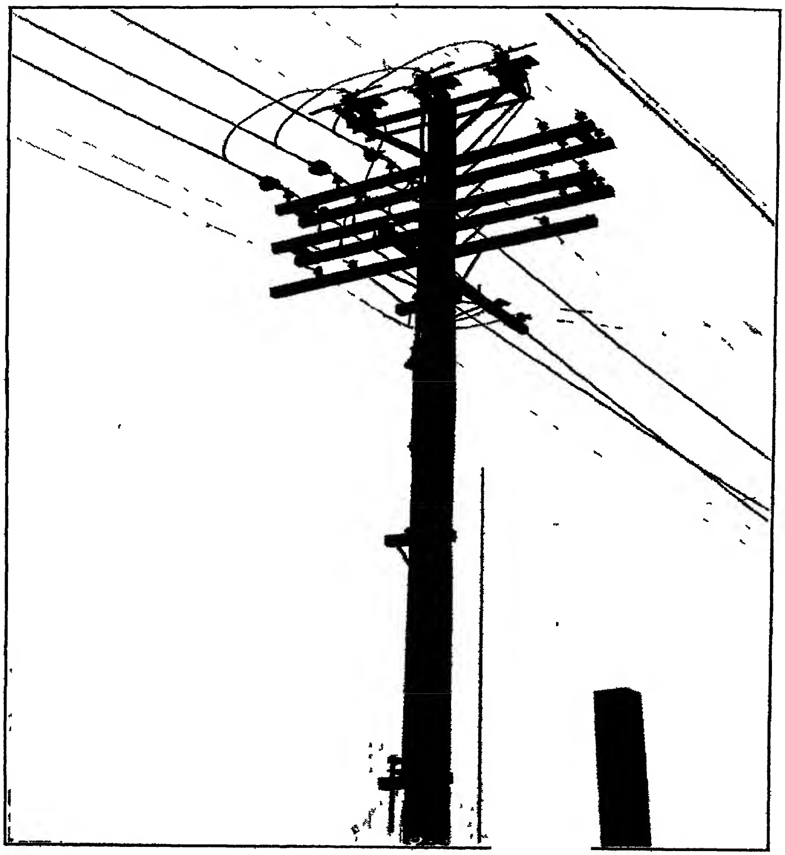


FIG. 323.—Pole-top switch.

The switch is installed on the extreme pole top above all wires in order to obtain the best clearance in case of arcs while opening the contacts. The circuit sectionalized may be seen on the top crossarm, with the two sections divided by means of pig-liver type of strain insulators cut into the conductors. The insulating section in the operating handle may be noted.

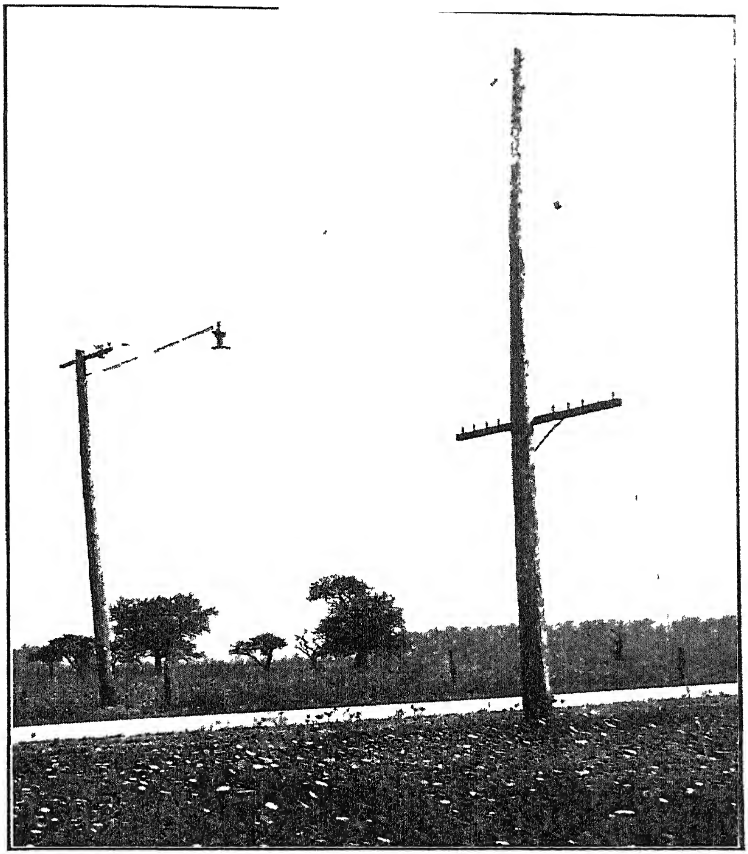


FIG 324a —Street-lighting lamp installations Center span. The transformer may be seen mounted on the crossarm supporting the supply circuit The trainer wires to the lamp are in two-conductor cable (duplex) carried on the messenger supporting the lamp, being attached by small metal clips The lowering rope for the lamp is carried back to the pole through cable rings attached to this same messenger The lamp is furnished with a cutout which disconnects when it is lowered The method of cutting the supply circuit with guy strain insulators may be noted, also the joint use of the span pole with the telephone circuits

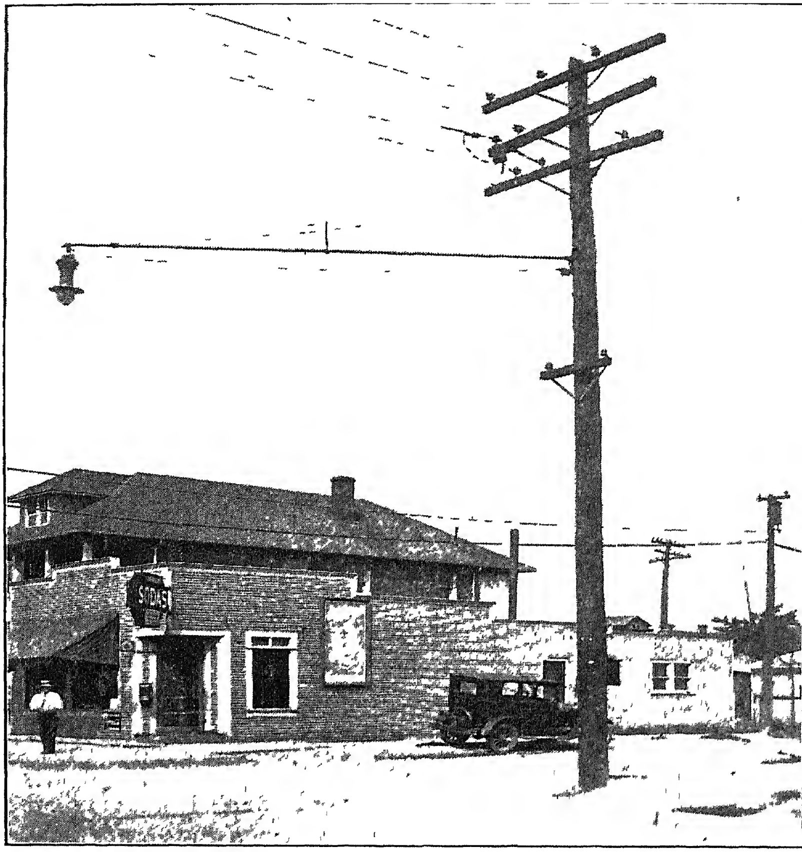
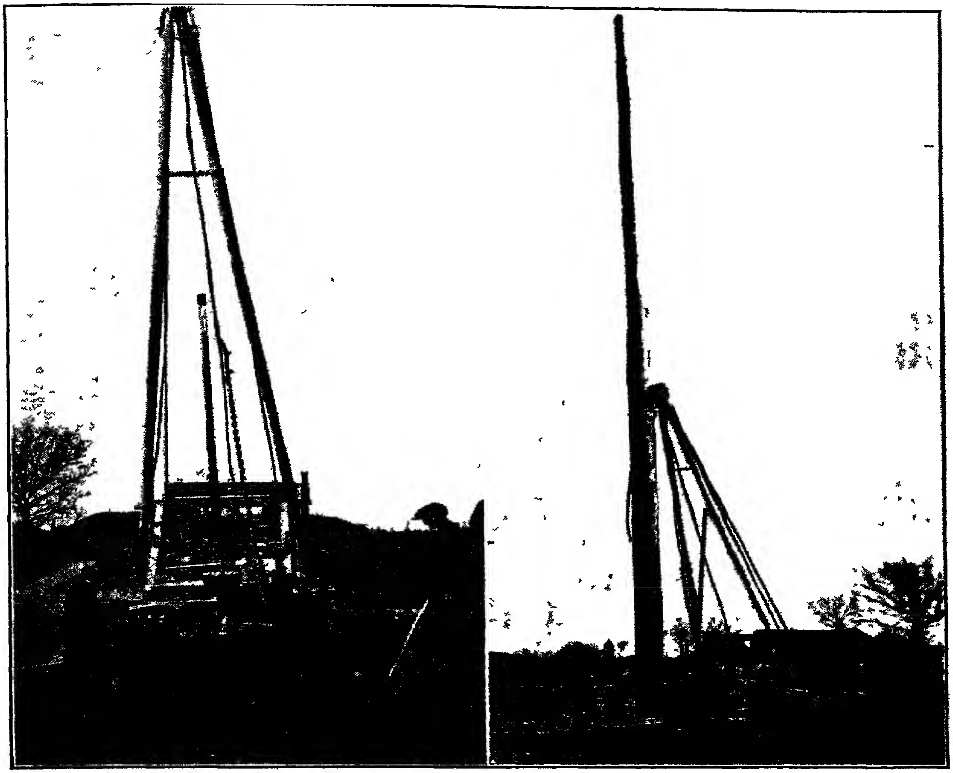


FIG 324b —Street-lighting lamp installation. Mast arm.

The supply wiring to the lamp in this case passes from the transformer along the underside of the crossarm (in wood moulding), down the pole, and out through the inside of the pipe to the lamp



(a) (b)

FIG. 325.—Setting pole with earth-boring machine.

(a), Digging the hole—the auger has just been brought up to the surface with a load of dirt and is spinning to throw it out away from the hole; b, setting the pole—the hole is completed and the derrick on the digger has raised the pole preparatory to dropping it into the hole.

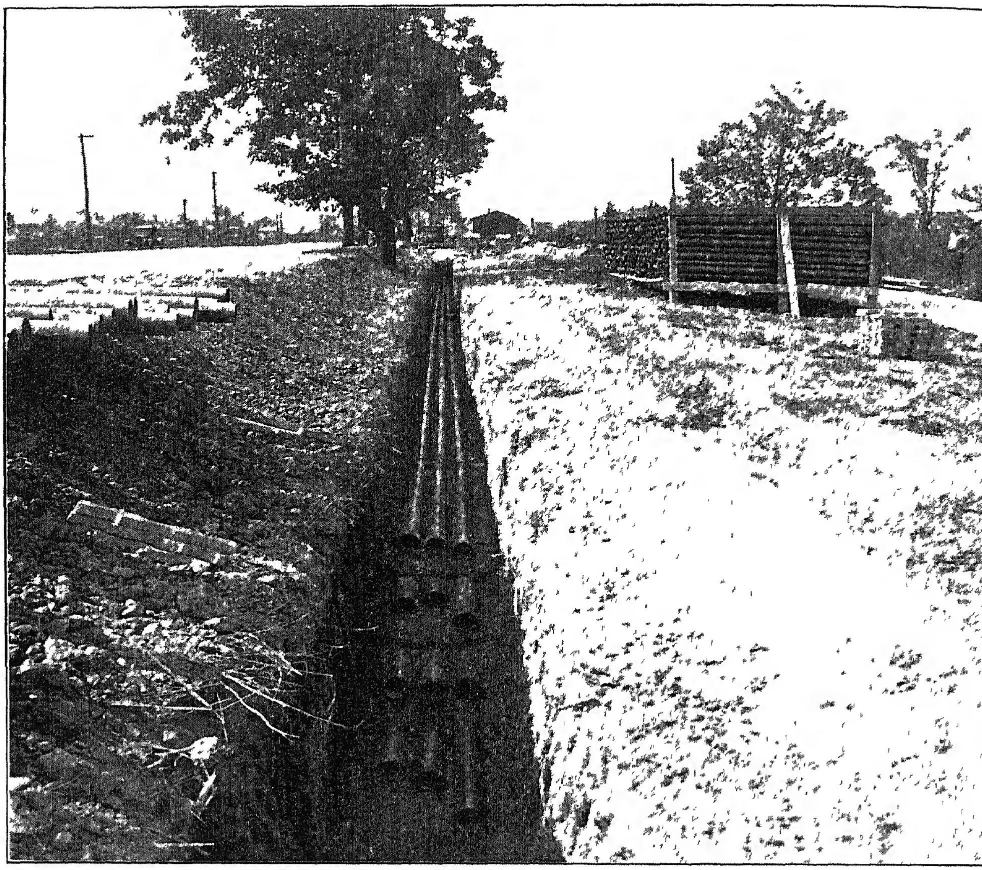


FIG 326 —Underground conduit construction.

A 12-duct conduit is being built with 4-in fiber duct The last layer of concrete over the top ducts is still to be poured Some of the concrete spacers used for holding the duct in position while the concrete is being placed and also additional sections of the fiber duct may be seen along the side of the trench The collars used to cover joints between lengths of the duct will be noted on the duct already laid. The details of this method of building conduit are indicated on Fig. 282.

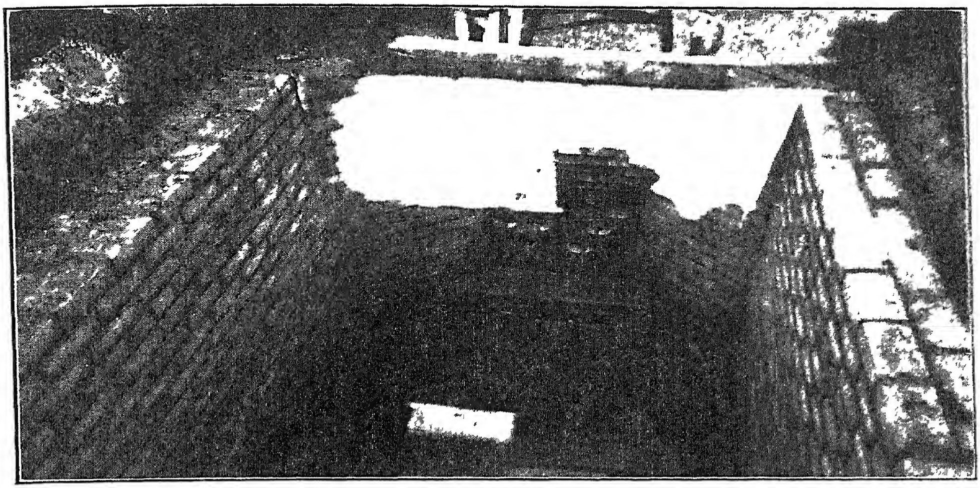


FIG 327a —Underground manhole construction—brick walls, showing conduit entrance

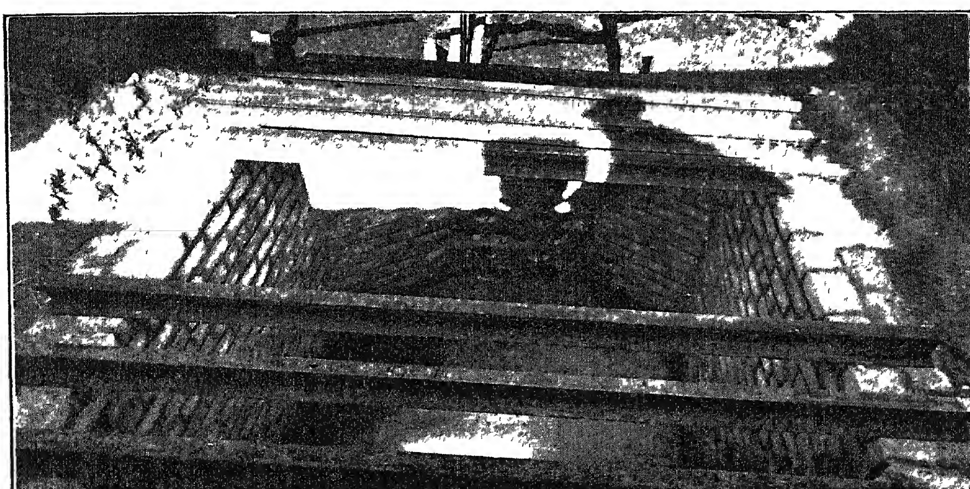


FIG 327b —Steel for roof—first course of steel rails in place for supporting brick roof

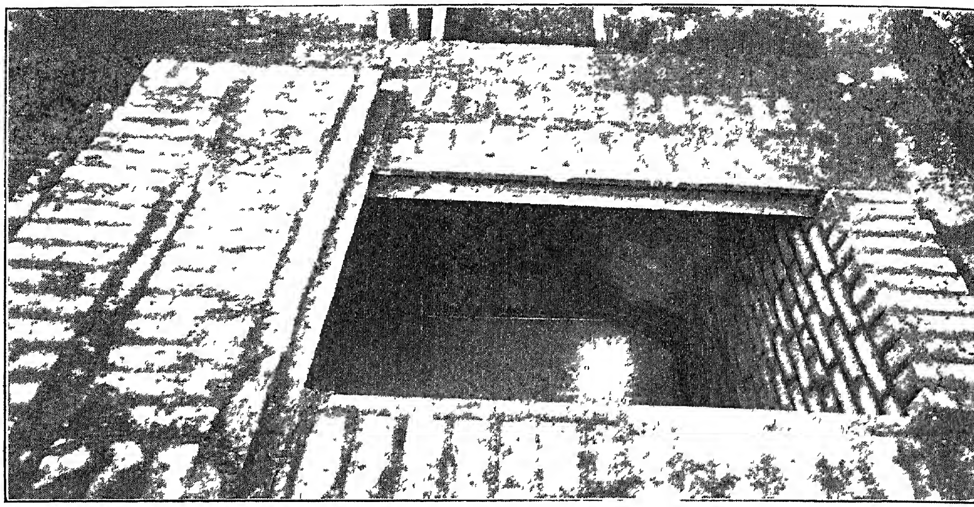


FIG 327c —Roof—first course is completed and part of the second course is shown at the left

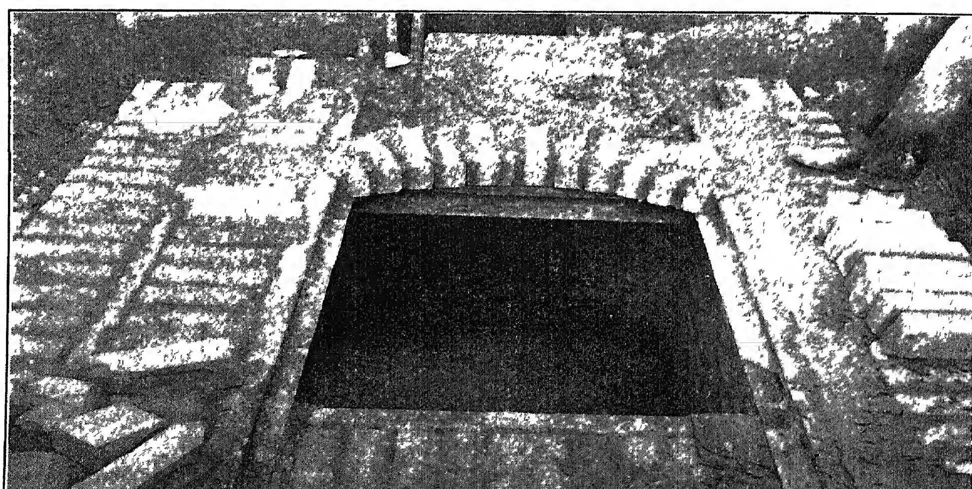


FIG 327d —Roof—second course is nearly completed Part of corbel to support chimney is shown

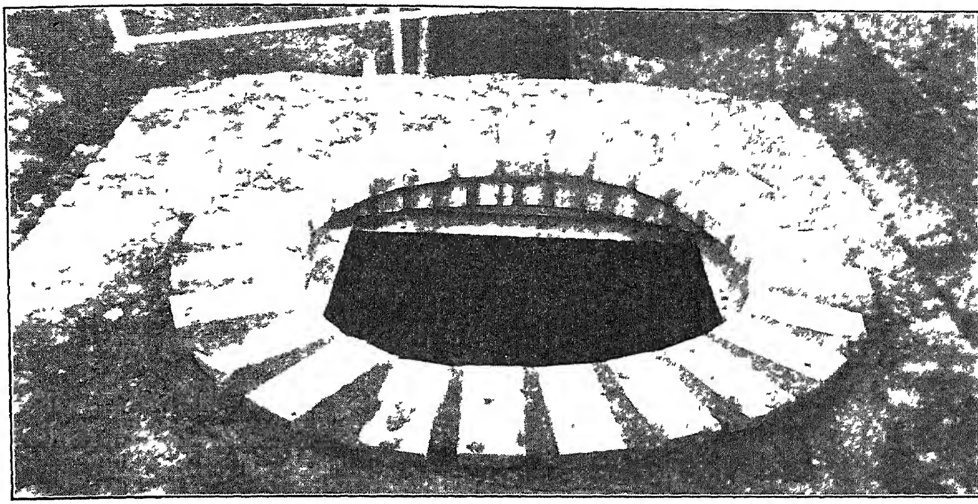


FIG 327*e* —Roof—first course of chimney is laid.

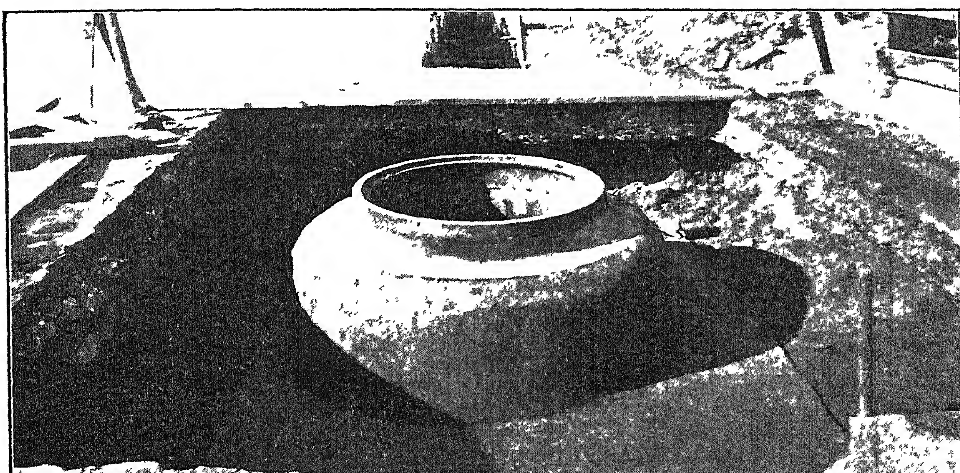


FIG 327*f* —Completed manhole—the frame for the cover is in place at the top The roof and sides of the chimney are plastered.

Details of manhole construction such as this are also shown in Figs 285, 287, 289, 290, and 292

CHAPTER XXVIII

STANDARDIZATION AND SPECIFICATIONS

Standardization of line construction and materials is one of the most important and profitable branches of the work of the distribution engineer. It is work in which the concrete results of intelligent effort can quite readily be shown—the value in dollars and cents of successful standardization is usually apparent.

By "standardization of construction" is meant the establishment, as far as is possible, of a single standard, for each unit of construction, such as line poles under various conditions, corners, transformer installations, cable poles, etc., so that, wherever such a unit occurs on the system, it will be constructed in the same manner and with the same materials. It must be recognized, of course, that many variations of conditions are met with in the field and some leeway must be allowed the construction man to use his judgment when he encounters conditions to which the specifications do not particularly apply. One of the prime objects of standardization, however, is to reduce such cases to a minimum and to serve as a guide to the construction man in the few cases which he must work out in the field. Ideas of different construction men as to proper construction are likely to vary quite widely. For example, in one case, before standardization had been worked out, seven different methods of hanging a transformer were observed within a ¼-mile radius. Some were not widely different from others but none were alike, although no one could be considered bad construction. Such conditions make for waste of time and material. If the transformers are all hung alike, the same material is taken out each time and installed in the same way, allowing the construction crew to emphasize speed and efficiency in construction rather than having to consider design. At the same time, the best design may be chosen as a standard and this may be further simplified and improved by careful study, the best ideas of all construction men and of the engineers being combined in this one standard. In the case mentioned above, for the eventual transformer installa-

tion adopted (after passing through several stages of development) there was used little more than half the material used in the *best* one of the seven previous installations and yet it had fully as good strength where strength was needed, and better clearances.

Standardization of materials goes hand in hand with the standardization of construction. For any unit of construction, the materials to be used are specifically designated and not left to the preferance of the construction man. Also, the number of such materials used on the system is reduced to a minimum thereby cutting the costs of purchasing, stocking, handling, and using.

Standardization of construction and materials is particularly applicable to line construction, more so than to other parts of the system, perhaps. The units of construction are relatively small, and many times repeated. A small savings on any unit is multiplied many times during a year. Labor operations may be systematized to good advantage, since similar operations are performed repeatedly.

Objections to standardization in general are sometimes raised, that it stifles initiative and is a hindrance to keeping up with the progress of the art. These objections are valid ones if standardization is handled as it sometimes is, by considering it as a specific task to be accomplished once and for all, permanent standards being set up. Such a standardization is likely to defeat its own purpose, first because it is hardly ever possible to establish on the first trial a standard which cannot be improved upon by further study, and second because new materials and designs are being continually brought out, many of which are marked improvement on older ones. Also, new conditions must be met as distribution systems develop. It is fairly obvious that standardization, to be effective, must be flexible. Provision must be made for continually studying the standards, with the view to improving them if possible. They should be subject to change whenever it can be shown that a permanent advantage is to be gained thereby. Initiative should be encouraged on the part of all those concerned with the work, in the suggestion of improvements which might be made in the standards. Individual initiative on the part of the construction men in departing from the established standards should not be tolerated, however. Once established, the standards should be strictly followed until such time as they are definitely changed, except of course in

cases of emergency or where unforeseen hazards are involved. On the other hand, too great haste should not be allowed in changing a standard which has been carefully worked out. Many times suggestions or criticisms will be received, which are apparently reasonable but which, after careful study, will be found to be based on prejudice or a wrong interpretation of observation. It almost goes without saying that for efficient results, standardization of any class of materials or construction should be the specific and continuous responsibility of one man in the organization who is given sufficient authority to enforce it. Divided responsibility in this matter only leads to confusion.

Standardization of Construction.—The chief advantages of standardization of construction have been mentioned above. The means for carrying out such work may depend somewhat on conditions on the particular system. There are, in general, three sources of information available from which assistance may be drawn:

1. Past construction on the system under study.
2. Suggested standards of the National Electric Light Association.
3. Construction used by other companies.

The first source named should be the first to be consulted, as a rule. There are usually special conditions peculiar to the particular locality, for which specific types of construction have been worked out. These are likely to be just as good at least as anything which can be imported from elsewhere. If there is more than one type used for the same purpose, the first step is to single out and make standard the one which appears best.

The Overhead Systems Committee of the National Electric Light Association has shown in its "Overhead Systems Reference Book" and subsequent serial reports, suggested standards for many units of construction. These are more or less general but do illustrate the use of materials which have been suggested as standards. They may very often be adapted to the particular conditions of a system.

The construction used by other companies is a good source for suggestions as to means of solving problems of new design or improving old ones. Care should be used, however, in following too blindly the lead of someone else. His conditions may be quite different from yours and may not conform at all to generally recognized or desirable standards.

After all available information is assembled, the standards which best suit the case may be selected. A thorough study of all details of the construction is then advisable for the purpose of:

1. Simplifying it as much as possible.
2 Making sure that it conforms with any codes or rules which may govern in the locality, with accepted good practice as to clearances and strength of parts, or with reasonable requirements for safety to the public, workmen, and the service
3 Using materials which are standard with the manufacturers and standard for use elsewhere on the system, if possible.
4 Making the design consistent as to strength, *i e*, reducing the strength of parts where an unnecessarily large safety factor is obtained and increasing those parts where the strength is relatively low. An ideal design would have uniform strength throughout, taking account of all probable variations in loading and the variations in character of materials. Strength tests on full-sized construction, simulating field conditions as far as possible, should be made where any doubt exists
5 Consulting with the construction men, to make sure that no practical difficulties in construction have been introduced.

In previous chapters, methods for computing strength of parts have been discussed, and also common standards of materials and construction have been shown. Safety Code provisions have been given in many cases. These will all be useful in a study of standardization.

Standards of construction can often be slightly changed to allow the elimination of certain materials from stock, other more standard materials being substituted. Standardization of materials and construction are thus interdependent. One cannot be carried to its fullest possible benefit without the other.

The matter of cooperation with construction men should be stressed. It is much easier to introduce new standards with their approval than against their wishes. There is usually a considerable amount of inertia on the part of men in the field against radically new ideas but, on the other hand, many valuable points may be learned, and incidentally many mistakes avoided, by giving the field men opportunity to express their views. Any really good change will stand the test of experience.

Construction Specifications.—Formal printed construction specifications are an essential accompaniment of standardization of construction. They are the means of keeping the construction men advised of the standards established. The details of their preparation must be such as will conform best with the method in which they are to be used and the organization of the construc-

tion personnel, keeping in mind the chief object of their existence. No definite rules can be laid down in this regard but some suggestions gained from experience with the preparation and continuance of such a set of specifications may be useful.

The size of the page may be such that the book will fit into the pocket if it is intended to be part of the field man's equipment (4¼ by 7¼ in. is convenient for this purpose). In using this size, the drawings will usually have to be on a somewhat smaller scale than if a larger sized page is used, but this disadvantage is offset by the convenience of the smaller book. Where the use is to be more as an office reference, a larger size, such as 8½ by 11 in., is probably preferable and, of course, this size can also be used for a field book if desired.

It is advisable to consider carefully the matter of quality of paper and binding. A book used in the field gets rough handling, and cheap binding and poor paper soon wear out. A loose-leaf binding is not desirable as it is too easy for pages to be removed and lost. On the other hand, it should be possible to replace pages for revision when desired. A post type of binder is satisfactory for this purpose.

The style of type used and the cuts for illustration should be clear and easy to read. Printed pages and drawings are preferable to blueprints for several reasons. Drawings for cuts are usually made several times larger than the finished cut. It is important that the lettering used be large enough and properly spaced to be clear when reduced in reproduction.

Specification books should be kept up to date, either by continuous revision, *i.e.*, whenever a change is decided upon, or by frequent periodic revisions, such as once a year. Otherwise, confusion is certain to result. Complete new pages are much preferable to attempting to make changes in old pages. It is a good plan to supervise the change of sheets in all books when issuing a revision, rather than depending upon the holders of the books to make the changes—usually the changes are not made if the latter method is used. Revisions and additions should be kept in mind when numbering the pages in the book. A consecutive numbering system is not satisfactory. One method is to give the pages the designation of the section and article of text which they contain.

The choice of material to be included in the specifications depends somewhat on their intended use. Some engineers make

the specifications a complete set of instructions to the construction men, including methods of construction, safety rules, and even some engineering data, as well as construction standards. Other organizations prefer to instruct their men in other ways on methods of carrying out the work, using the specifications merely as a handbook of standards. Whatever is included, however, should be expressed as clearly, definitely, and briefly as possible. It should be remembered that the construction man is not an engineer and he can only carry out such instructions as he can clearly understand.

A logical arrangement of the material is essential, so that any particular detail may be easily found. This is likely to be a somewhat difficult matter and a good index is an important part of the book. Two general methods of arranging material may be used. The first is according to type of construction, such as transmission lines, city distribution, farm lines, etc. Considerable duplication may be necessary with this arrangement but it gives a man complete information about the particular work he is doing when working on a line of any of the types covered. Another arrangement is according to the types of materials used, such as poles, cross-arms, transformers, etc. Less duplication is necessary with this method and, with a good index, it lends itself very well to general use.

As an example of the types of material which may be included and its possible arrangement, the tables of contents for a specification for overhead line construction and one for underground line construction are given below:

Standard Specifications for Overhead Line Construction

Table of Contents

Section A, General.

Article

1. Purpose of Specifications
2 Temporary Construction
3. Present Construction
4. Farm-line Construction
5 Definitions

Section B, Poles.

Article

1 Shaving
2 Branding
3. Roofing

4 Gaining
5 Locations
6 Spacing
7. Size and Class
  (*a*) Grade of Line
  (*b*) Minimum Height and Class
  (*c*) Dimensions
8. Setting
  (*a*) General
  (*b*) Depth of Setting
  (*c*) Self-sustaining

Section C, Cross-arms.
Article
1. Standard Sizes
2. Use
3. Attachment
4. Double Arms
5. Side Arms
6. Buck Arms

Section D, Secondary Racks.
Article
1. Standard Type
2. Where Used
3. Location
4. Corners, Dead Ends, etc.
5. Services
6. Details of Construction

Section E, Pole Hardware.
Article
1. Braces
  (*a*) Standard Items
  (*b*) Use
2. Blocks
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  (*b*) Use
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  (*b*) Use
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Standard Specifications for Underground Line Construction

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Section I, Underground Lines Materials.

Figures 328 to 335, inclusive, are reproductions of some typical pages in the specifications referred to above, showing style of type, arrangement, drawings, etc., which were used.

One further point should be noted in regard to construction specifications. For effective results, they must be followed up by field inspection of the work done. No matter how well written they may be they will not be clearly understood by all of the construction men and, in any case, some personal instruction is usually necessary in calling attention to the points specified, especially when changes in present practice are introduced. Much of the advantage of construction standardization is lost unless it is followed by careful enforcement.

Standardization of Materials.—In undertaking to standardize materials for line construction, several definite objectives should be kept in mind as follows:

1. Elimination of all duplication of materials. Several different materials may be used for the same purpose, each one quite satisfactory perhaps when considered alone. One or two may be selected, however, which will answer all the requirements of the work. For example, in one case, it was found that small bolts, small lag screws, and wood-screws were all being used, by differ-

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2. CLEARANCES

The clearance obtained between conductors of various voltages and other conductors, ground, supports, etc., shall not be less in any case than specified in the following tables. Where these specifications elsewhere call for spacings on standard construction greater than those shown in these tables, such spacings shall be used ordinarily, but, under no circumstances shall the clearance be reduced to less than that shown in the tables.

Conditions assumed—60° F., no wind.

(a) Wire Crossing Clearances in Feet

	WIRES CROSSING OVER					
WIRES CROSSED OVER	Signal	Supply Wires 0 to 750 V.	Services 0 to 750 V.	Supply Wires and Services 750 to 7500 V.	Supply Wires and Services 7500 to 50,000 V.	Guys, Messengers, Span Wires, Lightning Protection Wires
Signal (Including their cables and messengers)...	2	*4	2	4	6	2
Supply—0 to 750 Volts..	(4)	2	2	2	4	2
Supply—750 to 7500 Volts.........	(4)	(2)	(4)	2	4	4
Supply—7500 to 50,000 Volts.......	(6)	(4)	(6)	(4)	4	4
Trolley Contact Conductors.	6	6	6	6	6	4
Guys, Messengers, Span Wires, Lightning Protection Wires and Services (0 to 750 volts)....	2	2	2	4	4	2

*A clearance of 2 feet may be permitted where the supply conductor is above the signal conductors, provided the crossing is not within 6 feet from any pole concerned in the crossing, and the voltage to ground does not exceed 300 volts.

FIG. 328.—Sample page from a specification for overhead line construction.

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Figures in *Italics* refer to drawings.

A

	Section and Article
A Frames	B-8-c, B-8-2; J-2-b
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Arms—See "Crossarms"	
Arrangement of Circuits	I-1, *I-1-1*, *I-1-2*, *I-1-3*
Arresters, Lightning—See "Lightning Arresters"	

B

Banking Secondaries	I-5; P-14
Blocks	
—Spacing	E-2; *V-2-1*, V-9
—Transformer	C-1, C-2; P-11-b; *V-2-1*, V-9
Bolts	
—Eye	E-3; V-8-a, *V-8-1*

FIG. 329—Sample page from a specificaton for overhead line construction.

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Q—SERVICES

1. GENERAL

One service drop only shall be run to each building unless both single and three-phase service is desired, or special single-phase service, such as for single-phase motors, welders, etc., in which case separate services may be necessary.

Single-phase elevator motors and other single-phase motors, 5 H. P. or larger, usually require separate services and separate transformers. All such cases shall be referred to the Distribution Engineer for decision.

2. WIRES—MATERIAL, SIZE AND NUMBER

For services No. 2 or smaller —use soft (S), solid, weatherproof (W. P). copper wire.

For services larger than No. 2—use medium hard (M. H.), stranded, (W. P.) copper wire.

Open wire construction shall be used ordinarily.

In some cases where the required clearances and separations are not obtainable, it will be necessary to use multiple conductor cable. No. 8-3-conductor shall be used for all light two- or three-wire services (for two-wire, parallel two of the conductors) and No. 4-3-conductor for heavier services.

FIG. 330.—Sample page from a specification for overhead line construction.

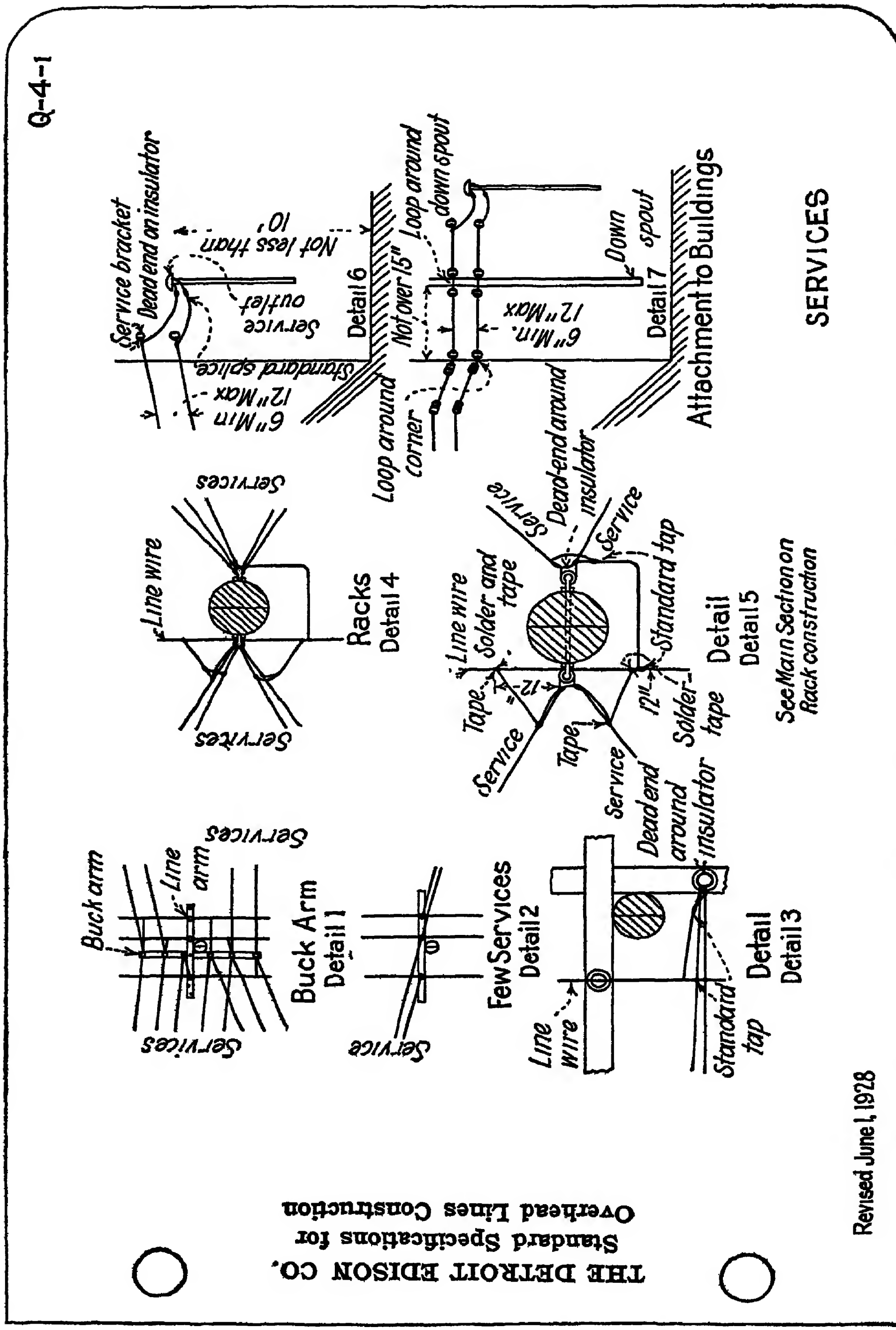


FIG 331.—Sample page from a specification for overhead line construction

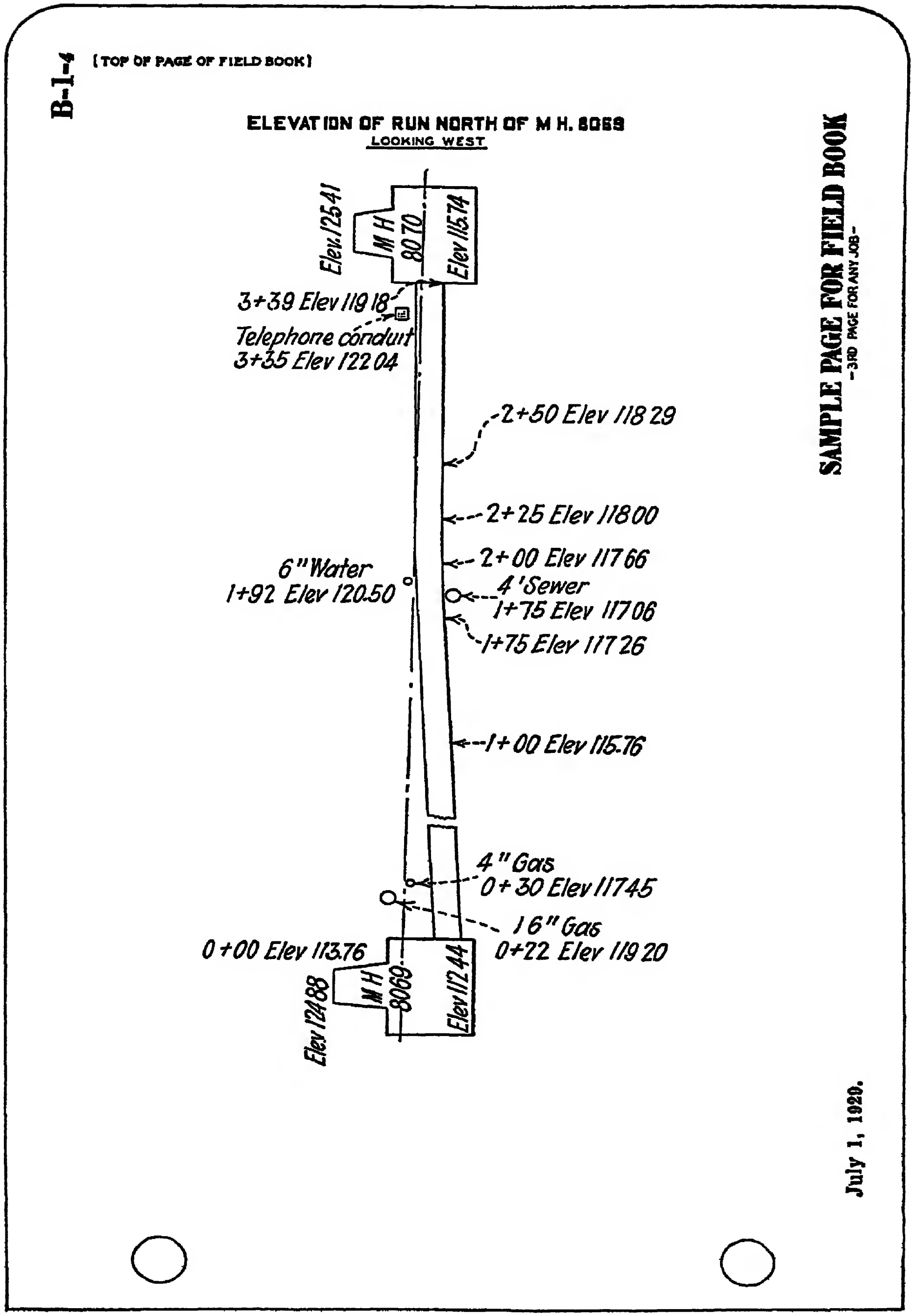


FIG 332.—Sample page from a specification for underground line construction.

B-4

4. MANHOLE CONSTRUCTION

(a) Shape and Size.

The standard shapes and dimensions of manholes are shown on the accompanying drawing as follows:—

Standard Straight Manhole	Page *B-4-1*
Standard 90° Manhole	Page *B-4-2*
Standard Offset Manhole	Page *B-4-3*
Standard 3 Way Manhole	Page *B-4-4*
Service Cable Manhole	Page *B-4-5*
Street Lighting Cable Manhole	Page *B-4-6*

These standards shall be followed whenever possible except for manholes in the vicinity of substation in which case the size and shape will be specifically shown on prints issued by the Underground Department engineers. If local conditions, such as surface or subsurface obstructions, do not allow the use of the standard shape or size, the manhole shall be made as near like the standard as possible and any such change shall be made only with the special approval of the Underground Lines Department engineers.

(b) Depth.

The manhole shall be of sufficient depth to allow the lowest duct in the lowest conduit to enter it at not less than 1 foot above the finished floor. For ordinary construction the clear head-room from floor to ceiling shall not be less than 5′-6″. Manholes for service cables, street lighting cables, etc., only may have a head-room of 4′-0″. The head-room shall be sufficient to allow the highest duct to enter not less than 1 foot below the ceiling.

Care should be taken in laying out conduit and manholes that the depth necessary will not be too great to allow free drainage to an adjacent sewer system.

FIG. 333.—Sample page from a specification for underground line construction

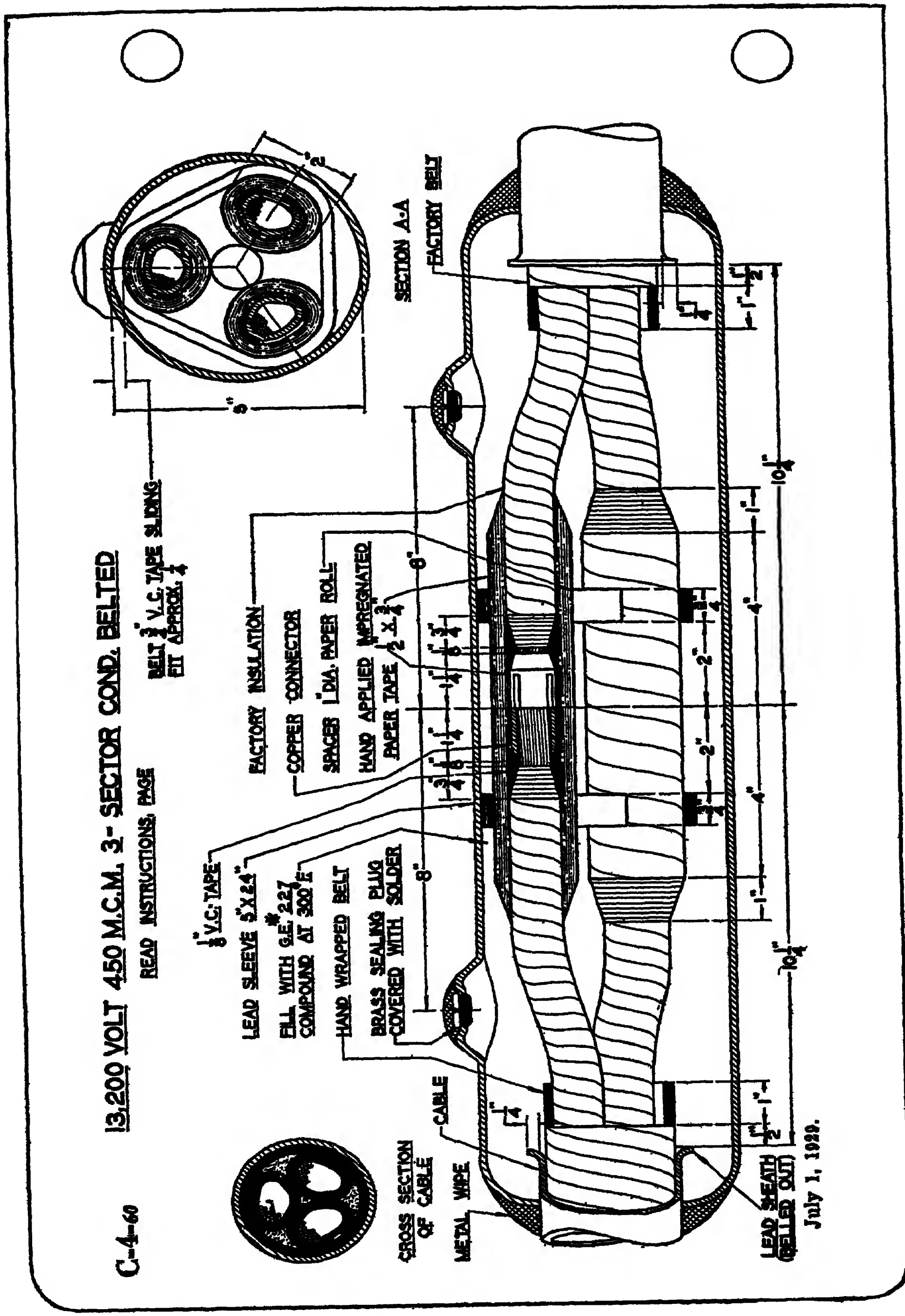


FIG 334 —Sample page from a specification for underground line construction

C-4-60

OPERATIONS IN MAKING

13,200 Volt—3 Conductor—450 M.cm.—Sector—Belted Type—Cable Joint

(Refer to detailed description of operations in paragraphs 2 to 30 inclusive, Pages C-4-a. Numbers following each operation refer to the particular paragraph in which it is described.)

(a) Train cable. Adjust tag (Paragraph 2).
(b) Prepare lead sleeve. Slip lead sleeve on cable (Paragraph 3).
(c) Establish center line of joint. Cut cable to fit (Paragraph 4).
(d) Measure 10" away from center line on each cable end. Crease sheaths (Paragraph 5).
(e) Shave cable sheath near crease. Smear shaved surfaces with stearine (Paragraph 6).
(f) Remove sheath back to crease. Bell ends of sheath ¼" (Paragraph 7).
(g) Remove belt insulation to ½" from end of belled out sheath. Cut off ends of insulation square (Paragraph 8).
(h) Cut off fillers square as closely in crotch as possible (Paragraph 10).
(i) Phase and match conductor (Paragraph 11).
(j) Bind conductor insulation on each conductor with cord about 2¾" from the end to prevent unwrapping (Paragraph 11).
(k) Remove conductor insulation on each conductor for a distance of 1⅜" from the end, cutting off ends of insulation square (Paragraph 14).
(l) Pencil conductor insulation back ¾" and smooth with No. 2 flint cloth ¾" wide. Cover pencil with varnished cambric cloth as a protection in succeeding operations (Paragraph 15).
(m) Wipe end of conductors clean and fit into copper sleeves. Protect the penciled insulation and conductor against scorching and accumulation of solder by winding on 8 or 10 turns of gilling twine, starting about ⅛" from the end of the copper sleeve and winding part way up on the pencil. Sweat conductors into sleeve. Dress down rough surfaces and wipe clean (Paragraph 16).
(n) Spread the conductors (Paragraph 17).
(o) Remove the gilling twine and varnished cambric cloth from the penciled insulation of one conductor. Wipe the penciled insulation, copper sleeve and conductor thoroughly with a strip of dry cloth (Paragraph 18).
(p) Apply ⅛" varnished cambric tape insulation in the depression between copper sleeve and penciled insulation. Build up flush with copper sleeve. Smear hot tape impregnating compound over it to fill all possible voids or depressions (Paragraph 18).

July 1, 1929.

FIG 335.—Sample page from a specification for underground line construction

ent men, for the same purpose. All varieties but one were eliminated.

2. Elimination of all unnecessary sizes or designs in any one kind of material, making one size serve the purpose of several if possible. For example, in one case it was ound that ½-in. lags were being used in sizes from to 6 in. (in ½-in. steps). The 5-in. length was found suitable for all purposes, and five sizes were discontinued. As another instance, some companies find it practicable to carry machine bolts only in even lengths (10, 12, and 14 in., etc.) rather than all lengths (10, 11, 12, and 13 in , etc.).

3. Elimination of obsolete and out-of-date materials and special materials as far as practicable, adopting generally accepted standards when possible. The National Electric Light Association suggested standards are a good guide in this regard. They are, as a rule, standard with most manufacturers. In addition to these, there are many other sizes and designs of materials which are more or less standard with the manufacturers. It is preferable to use these if possible rather than to adopt special designs. It is not wished to intimate that new ideas for materials should be suppressed. Real improvements in old designs or new materials which are superior to the old ones are always welcome and represent real progress in the art. Care should be taken, however, that a real improvement is made and one which is likely to be generally recognized as such, rather than merely a design which will be "different." Special designs which are used by only one consumer are usually costly, since the manufacturer cannot give them the benefit of the economies realized by large production and has to include in the price his costs for special dies, tools, etc., and special handling. It will often be found, on careful analysis, that a new design will be not enough better than some standard design to warrant the extra cost. On the other hand, of course, if a new design is considerably better or simpler than an old one, it may represent a saving in the long run Also special conditions of use may require special treatment in some cases.

Another consideration in the matter of special designs is that some manufacturers put out materials with special features which may not, of themselves, be very essential or important, but which serve as selling points. If the material with these features is adopted as a standard, the one manufacturer is favored and

competition is eliminated. It is well to scrutinize such features carefully to see if they are really essential improvements.

4. Elimination of materials which have small use. There is an infinite variety of "gadjets" on the market which are offered as being just the thing you need to do this and that. It may be perfectly true that they will do what is claimed, but on careful consideration it is realized that their use will be very small, perhaps only occasional. It is foolish to clutter up the warehouse with stocks of these materials when the purpose can be served in some other way with standard materials, even though the cost of using the standard material may be somewhat more than the special material in the few cases in which it is needed.

The same principle may be applied to the elimination of materials which may be generally recognized as standard and have considerable use on some systems but are rarely used on yours. An example is the so-called "side arm." On a system where a large amount of side-arm construction is used, a stock of arms specially bored for the purpose is obviously advisable. Where side arms are used only occasionally for special purposes however, it may be found more convenient to rebore a standard cross-arm for the purpose when needed.

5. Simplification of line construction, whereby not only excess material may be eliminated, but some types or sizes of materials may be discontinued, the ones chosen as standard being made to serve as many purposes as possible. For example, some companies use entirely different cross-arms for high voltage lines (such as 24,000 volts) than they do for distribution. If a heavy distribution arm is carried for use on heavy lines, it may often be adapted to the high voltage line also.

6. Obtaining for the materials adopted as *standard* the designs and the quality of material best suited to the purpose.

Standardization of materials carried out on the above basis will be almost sure to be productive of real and considerable economies. From the point of view of the storekeeper and the construction crews, the elimination of a considerable number of stock items has the following benefits:

1. It reduces the amount of investment in stock, which also naturally reduces the interest, taxes, etc., on that investment. A reduction in *number* of stock items does not, of course, produce a proportional reduction in total stock investment. If one insulator is adopted as a standard where three or four different styles

were previously used, the stock quantity of that one must usually be larger than that of any *one* of the four, but it probably need not be as large as the *sum* of all four. There is an appreciable net saving.

2. The required warehouse space and facilities are reduced.
3. The cost of handling materials is cut down.
4 The cost of book-keeping, stock records, etc. is proportionately lessened.
5 The stock necessary to carry on the line wagons is reduced.
6. Writing of bills of material and estimates is simplified.
7 Line work and maintenance is simplified.

Some study is often needed on the question of reduction of stock *versus* increased cost of materials. For example, two sizes of a certain article are used. The larger one is necessary but it may also be used in place of the smaller, if desired. The question is whether the reduction in the cost of carrying the extra item will offset the additional cost of the larger item where the smaller would suffice. An evaluation of the storeroom cost of carrying a stock item of a certain class is a great help in deciding such a question.

From the point of view of the purchasing agent, standardization of materials accomplishes several important results:

1. It allows materials to be purchased in large quantities, thereby usually reducing the price.
2. It allows materials to be purchased which are standard with the manufacturer and on which the prices are therefore likely to be considerably lowered by the economies attendant on quantity production of a standard article.
3. It allows competition between manufacturers who make the standard items, which usually results in lower prices. The standardization should be so carried out that, as far as it is practicable, at least two sources of supply will be available for every item of material, in order to allow for competition.
4. It reduces cost of records and other office routine by reduction of number of items purchased.

In regard to standardization of materials as in regard to standardization of construction, the objections are sometimes raised that it will hamper the workman who knows what he needs to do a good job, and hinders the introduction of new ideas and new materials. The first objection may hold true to a limited extent, but if the standardization is intelligently carried out and

with due regard to the requirements and habits of the construction man, the advantages will far outweigh this disadvantage. The second objection will be avoided if the standardization is made flexible and is continuously studied for changes of improvement.

That very desirable results can be accomplished by standardization of materials is exemplified by the experience of one large power company. Good materials had always been used and construction was good, but the matter of details of design and materials had been left to the individual construction foremen to quite an extent, as is usually the case where standardization has not been introduced. By careful study of each item of material (together with details of construction) approximately *one-half* the number of stock items of overhead line material was eliminated. The remaining materials were improved by introducing manufacturers' standards and better designs where possible. Some of the reductions made by the original study were as follows:

Class	Number of items before standardizing	Number of items after standardizing
Poles	28	18
Cross-arms	12	7
Pins	16	7
Braces	9	5
Insulators	20	11
Bolts	44	25

After the first standardization, further simplification was later made. Cross-arm items, for example, were reduced to 3, pins to 3, and insulators to 8. It is evident that such reductions as these illustrated cannot but prove beneficial.

Unfortunately, there has been as yet little real standardization of national scope in the matter of line materials. The National Electric Light Association Overhead Systems Committee has published in the "Overhead Systems Reference Book" and later serial reports, suggested standards for major items of material, but these have not been officially offered as standards. The

matter of official standards has been left to the American Standards Association, whose work of necessity must be very carefully and thoroughly done and hence take considerable time. The specifications of the American Society of Testing Materials are very useful as standards for the quality of certain materials such as copper, steel, etc., and there are standard specifications for hard, medium, and soft-drawn copper wire, stranded wire, rubber-insulated wire, galvanizing, etc. The American Institute of Electrical Engineers also has a series of standards which includes various grades of copper wire, aluminum wire, and insulators, referring especially to methods of testing. Anyone interested in standardization of line materials would do well to become familiar with the work of these various organizations and keep in touch with their future efforts, as development work in this line is being constantly carried forward.

National standards for these materials are, of course, desirable as they will allow the manufacturer to eliminate a large percentage of the items which he now must carry. For example, there would seem to be little reason why the number of different types and sizes of secondary racks used should be more than possibly 6 or 8 at most and yet one manufacturer lists more than 25. Reduction in the number of different kinds should mean reduction in price for the standards retained. In considering standard items at present, however, it should be remembered that for most of the types of materials, satisfactory standardization has not yet been finally accomplished—it is still in progress The National Electric Light Association list of suggested standards, while as good a compilation as now exists, is still in course of preparation and in some instances is perhaps, at present, more limiting than is warranted by circumstances. With cross-arms, for example, the National Electric Light Association cross-section for ordinary low voltage arms has been 3½ by 4½ in. Many companies have used 3¼- by 4¼-in. arms for years, they are suitable for their purpose and cost less than the "standard" since they are just as standard an item with the manufacturers, who produce them in large quantities. In such cases, the increase in cost of adopting a suggested standard is hard to justify, unless it can be forseen that eventual economy may result. In other words, in the present condition of standardization, it is desirable to conform with the standards proposed by the various national organizations if practicable, but one must also take into

consideration the matter of whether such standards will accomplish for him a reduction in cost or an improvement in construction with the increase in cost, allowing of course for the possibility of reduction in price if the manufacturer can concentrate on one standard item instead of several.

In selecting standard materials and approving the particular items offered by different manufacturers, the value of laboratory and field tests should be emphasized. Such tests will often show weakness in the material or design which is not at all apparent from visual inspection. The field test under conditions simulating actual operating conditions as far as possible is preferable.

Another important requirement for effective standardization of materials is cooperation between the engineer and the storekeeper, purchasing agent, and construction men. The storekeeper can be of great assistance in enforcing strict adherence to standard materials, reporting defects in materials or designs observed or complained of by construction men, reporting slow moving or obsolete items of stock, and disposing of non-standard materials which may be used up. The latter is an important feature of the work of standardization. Many materials which are eliminated as standards in reducing the variety of sizes, etc., may still be used up without difficulty. With other materials, such as those found too weak or of too short life for the service required, other disposal is preferable. It sometimes requires considerable judgment and consideration of costs to decide what disposal should be made of non-standard items.

The purchasing agent can cooperate by referring all materials and designs to the engineer for approval The most effective results in this work can be accomplished if the fields of the engineer and the purchasing agent in this regard are kept entirely distinct, the former having approval of materials as to design and quality, and the latter the choice of the source of supply, subject to such approval.

Specifications for Materials.—One of the greatest aids in standardization of materials is the preparation of formal specifications for such materials as can be so treated, such as poles, crossarms, wire, etc. With such specifications, the purchasing agent can have a greater choice of sources of supply, and all manufacturers know exactly on what basis they are quoting. They also give a measure which can be applied to the material after it is received.

Figure 336 is a reproduction of such a specification, as a typical example.

In the preparation of a specification, it should be kept in mind that the purpose is to tell the manufacturer just what is wanted, clearly and plainly, so that no misunderstanding is possible The shorter the specification, the better, provided it clearly describes the qualities expected in the material. Where other standards are used as a reference, such as American Standard Testing Materials Specifications, they need not be copied, unless explanations or exceptions make it necessary.

Where sizes are specified, *tolerances* should usually be included in the specification. It is impracticable to make any dimension absolutely exact—expansion or contraction of material with temperature or degree of moisture changes all dimensions. By specifying tolerances, the degree of inaccuracy of manufacture may be limited. The tolerances should be as large as the circumstances of use will allow, since, as a rule, the greater the accuracy the greater the cost. With porcelain materials, great accuracy is, as a rule, impossible since the material changes considerably in being fired. With wood, fairly large tolerances are necessary to allow for changes with moisture content and natural inaccuracies in manufacture. Typical tolerances are shown on a number of drawings in previous chapters, such as Fig. 186, etc.

Inspection of Materials.—Specifications for materials can be made really effective only if they are followed up by careful inspection of the material, either at the manufacturer's plant or on delivery. If such inspection is not carried out, there is no assurance that the materials received are what is desired. Even when the manufacturer conscientiously tries to live up to the requirements, there are sometimes mistakes made which may produce results far more costly than the expense of inspection would have been. It seems obvious that there is little use in setting up requirements to be met unless a check is made to see that they are met.

THE DETROIT EDISON COMPANY
SPECIFICATION

Specification 52
Revised March 29, 1927

UNTREATED WOOD CROSS ARMS

1. MATERIAL

Untreated wood cross arms, Douglas Fir.

2. USE.

Overhead lines construction.

3. GENERAL

Cross arms shall be made from straight grained, thoroughly air-dried or kiln-dried, yellow Douglass Fir The style and detail number shall be specified on the Purchase Order

4 DEFECTS

The cross arms shall not contain any of the following defects·

(a) Annular Rings. Annular rings counted radially averaging less than 8 per inch.

(b) Checks. Checks exceeding 12 inches in length, ¼ inch in depth, or 1/16 inch in width

(c) Grain Grain, as shown by the medullary rays of the wood, which departs from parallelism with the axis of the cross arm by an amount greater than 1 inch in 1 foot of length (approximately 5 degrees)

(d) Knots. Loose or unsound knots. Knots exceeding ¼ inch in diameter in any 3-inch longitudinal section having pin or bolt hole at its center Single knots or a plurality of knots in any 6-inch longitudinal section having a total diameter in excess of ¾ inch.

(e) Loose heart.

(f) Pitch Pockets. Pitch pockets exceeding 8 inches in length or ¼ inch in width Pitch pockets exceeding 4 inches in length or ¼ inch in width which enter a pin or bolt hole on the top of the arm. Single pitch pockets which extend through the arm appearing on more than one surface.

(g) Rot. Rot, dote or red heart.

(h) Sapwood Sapwood in excess of 25 per cent in any cross section taken in a plane perpendicular to the axis of the cross arm

FIG. 336.—Typical example

Specification No. 52
Page 2

4 DEFECTS—Con't.

(i) Shakes. Cracks or splits concentric to the annular rings of the wood

(j) Wane Bark or reduction of cross section due to removal of bark.

(k) Warp Warp exceeding ¾ inch for cross arms 8 feet or less in length, and 1 inch for cross arms 10 feet in length The warp shall be determined by measuring the offset between the cross arm and a straight-edge laid lengthwise on the concave face of the cross arm.

(l) Worm holes.

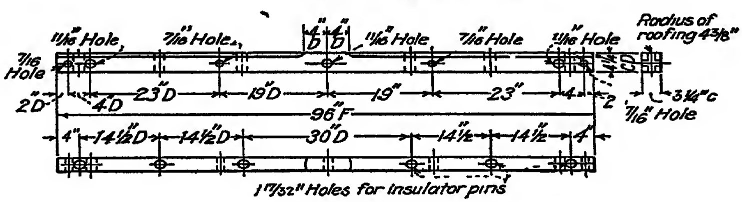
5. WORKMANSHIP AND DIMENSIONS

Cross arms shall be finished smooth and true All bolt and pin holes shall be smooth and all burrs removed where bits have broken through Brace bolt holes shall not be drilled through the pin holes. The dimensions for details 2, 3 and 4 shall be as shown on pages 3, 4 and 5. The allowable variations shall not be exceeded

6. REJECTION

Failure to conform with this specification shall constitute cause for rejection

DETAIL—2
Standard 1½"—6 Pin 3¼" x 4¼" x 96" Cross Arm
Stock No 4102-002



Allowable Variations		
	Over	Under
C	1/16"	1/16"
D	1/8"	1/8"
F	1/4"	1/4"
CD	1/16"	1/8"

of a specification for material.

CHAPTER XXIX

JOINT CONSTRUCTION WITH COMMUNICATION CIRCUITS

The joint use of poles by power supply circuits and communication circuits, especially the local distribution circuits which serve the same customers, offers such seemingly obvious advantages that there is little doubt that it will be the common practice in the future in most localities. Such construction is quite general now and its use is rapidly increasing. There are certain apparent limitations to joint use however, and various problems arise in connection with joint use agreements and construction. It is the intention of this chapter to discuss briefly these points with which the distribution engineer should be familiar in this connection.

The advantages of joint use are clearly apparent. One pole line may be built instead of two, thereby making a better appearance on the street or alley and saving the cost of one line. In addition to this it is often easier to maintain proper clearances between the service wires and circuits of the two utilities when both are carried on the same pole line than when each occupies its own side of a street or alley—the service wires of one do not have to cross over or under the line conductors of the other, see Fig. 337. Where both lines must be built on the same back lot line or easement, joint use is clearly the best arrangement since practically the same clearances and grade of construction are required whether the wires are on the same or separate poles. These advantages are obvious and need no further discussion.

The disadvantages of joint use are not so well recognized, however, but are sometimes of considerable importance. In the first place, the saving in cost of construction is not always what it seems and usually is not equal to the cost of the second line of poles. The following additional costs must be considered:

1. The loading on the pole will be heavier than with either of the utilities alone. If the load of either is such as to be anywhere near the limit of strength of the poles normally used, the poles

for the joint line must be either of larger diameter or be more closely spaced.

2 The Safety Code requires a higher grade of construction under certain conditions for joint use than would be required for separate lines. This may necessitate heavier poles.

3. The clearances required between the conductors and equipment of the two utilities is likely to necessitate the use of higher poles for the joint construction than would be required for either if on separate leads.

4. The presence of foreign wires on the pole is very likely to cause an increase in the cost of construction and maintenance for both utilities.

5. The rearrangement of old lines to provide proper clearances for a second utility's equipment may not be a small item.

6 The routine necessary for interchange of permits, keeping records of poles jointly occupied, and collecting rentals or portions of construction costs, all involve an expense not incurred with separate lines. In addition, closer inspection of construction is likely to be advisable to insure the maintenance of safe conditions.

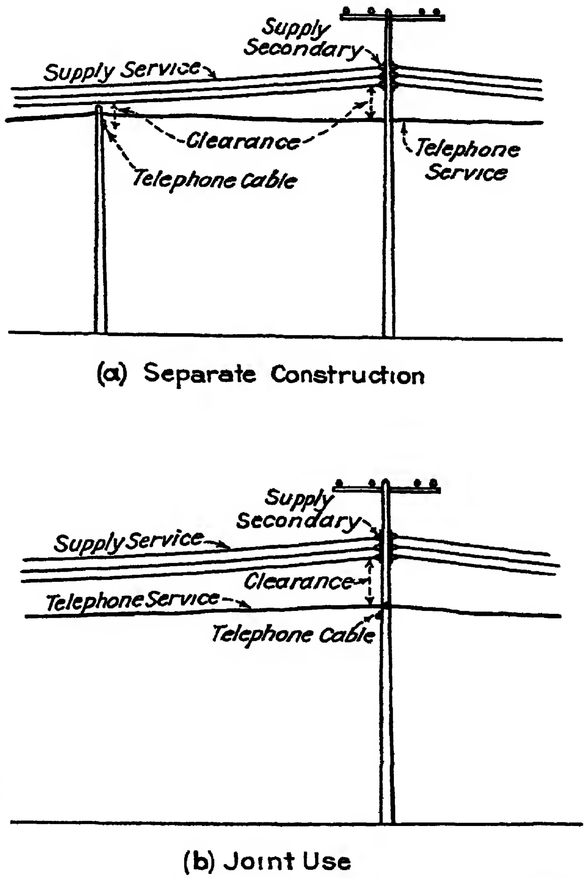


FIG 337 —Clearances of service wires with separate construction and with joint use

In addition to the above items of cost, the matter of voltage limitation is a very important consideration. At present the communication utilities indicate 5,000 volts as the limiting voltage of supply circuits with which they consider it advisable to

enter into joint use. This limit is based on the rating of the protector ordinarily used on telephone services. The tendency in power distribution is everywhere toward higher voltages as loads increase, and 5,000 volts is not now considered a high distribution voltage. It seems very probable that the future will see a general use of voltages greater than 5,000. On the other hand, the communication utilities must be allowed to judge the requirements and necessities of their own service. This principle is enunciated in the "Principles and Practices for the Joint Use of Wood Poles" prepared by the Joint General Committee of the National Electric Light Association and the Bell Telephone System. In certain localities, joint use with higher voltage lines has been entered into, and it seems probable that means will eventually be found whereby joint use with higher voltages will be made generally acceptable. At present, however, the communication utilities are preferring the 5,000-volt limit as a general rule, and this should be remembered when entering into a joint use agreement at a lower voltage. No matter what the distribution voltage may be now, it is well within the realm of probability that conditions may necessitate a change to higher voltage at some future time. Whether or not the voltage limitation is stated in the agreement, until the present attitude of the communication utilities changes, opposition may be expected to raising the supply circuit voltage above 5,000 volts. This condition should be understood. Another factor in the situation is that indicated in Item 2 above, under "Additional Costs." For higher voltages, the Safety Code specifies higher grades of construction (see below under "Construction Requirements"). The changes to a higher voltage may involve an appreciable amount of rebuilding if joint use is continued.

Another factor to be taken into account with joint use, especially at the higher voltages, is the possibility of increase in inductive interference problems. Such troubles are likely to increase as the separation between circuits decreases and additional expense may be involved in correcting them.

It is not intended, in enumerating the disadvantages above, to indicate that joint use is not advisable. On the contrary, for many conditions it is to be recommended. It is merely wished to point out some of the conditions involved which tend to offset the seeming advantage in all cases and which may make its use inadvisable in some instances.

In general, joint use is to be recommended for city and suburban distribution circuits, particularly the branch lines in streets, alleys, or easements from which the customers' services are taken. For these, the poles used for the power circuits are quite likely to be high enough and strong enough to accommodate telephone circuits without change in size or class.

For main feeder circuits, the advantages of joint use from the standpoint of economy are more questionable, since the pole lines carrying such circuits are more likely to be heavily loaded. From the standpoint of appearance, however, it may be advisable, even if no economy results.

For rural or farm lines, joint use is not so likely to be advantageous. For such lines, the supply circuits can often use long spans and short poles, services being few, and the addition of communication circuits is likely to introduce greater increase in cost due to higher poles and shorter spans than the cost of the separate communication line on short poles on the other side of the road. Also, on farm lines there is greater possibility of higher distribution voltage being necessary than in the city.

For communication toll circuits, separate lines are advisable on account of their higher service requirements. Also, for supply transmission circuits, separate lines are usually to be recommended.

Joint Ownership versus Rental.—The division of cost of poles in joint use is accomplished, in general, in two different ways. In some cases, each pole occupied jointly is *jointly owned, i.e.,* each utility owns a share of the pole. The utility erecting the pole is paid a part of its cost by the other who thereafter partakes in the rights and responsibilities of the ownership. This plan avoids possible discussion as to which utility shall erect and own any particular line of poles. On the other hand, many utilities prefer to retain complete ownership and control of at least a part of the number of poles jointly occupied. This is especially likely to be the case where joint use is to be entered into between two utilities, one of which owns a large majority of the poles already in place which are suitable for joint use. For such cases a space-rental agreement may be used, each utility owning its own poles and renting to the other a certain specified space thereon at a stipulated yearly rental. Usually, with this form of agreement, some provision is included for eventually equalizing the ownership of poles so that the yearly rental payments from each company to the other will very nearly balance each other.

Some of the older forms of agreement were based on contact rental, *i.e.*, a specified rental for each conductor or other attachment. Such an arrangement however is not logical and involves a vast amount of work in keeping records of contacts and payments therefor. Space rental is much more consistent with practical conditions (since the same pole will be set regardless of the number of conductors, within certain limits) and is much simpler to use.

Features of Agreement.—It is not intended to go into details in regard to contracts covering the joint use of poles. Some companies get along without any formal contract but it is usually considered advisable to have a definite agreement covering the various features of the case. Some of the more important will be pointed out briefly with especial reference to the space-rental type of agreement, although some of them apply also to joint ownership.

1. It is well to stipulate in some way what poles are included in the agreement. In some cases it may be wished to reserve certain types of lines. In one type of agreement, only the methods by which poles may be brought under joint use are included, the individual permit issued for each pole so used being the only actual contract covering the use of that pole. Whatever form is used, it should be fundamentally recognized that each utility should be the judge of whether a particular circuit of its own is suitable for being brought into joint use, subject of course to the necessities of the case and the rights of the public to receive service from the other utility.

2. Where old pole lines must be reconstructed or rearranged to provide for joint use, the method of division of cost for such rearrangement should be stipulated. In some cases, the theory that the owner as the renter should put his house in order for the lessee, places the full cost on the owner of the pole. Another theory is that the cost of rearrangement should be divided between the two parties on the same basis that the cost of the pole is divided (in computing the rental).

3. Provision should be made that all construction on the pole should at all times be maintained to the satisfaction of the owner (under space-rental).

4. Provision should be made for advance notice from each utility to the other of intention to build or alter any pole line, so that opportunity is afforded for providing for joint use if

desired. Such giving of notice may hamper the furnishing of prompt service to customers if not limited to some extent. If proper cooperation is offered by both parties in general planning, and typical construction details are worked out beforehand, a large percentage of cases can be handled very promptly when actual construction is decided upon. Advance notice can sometimes be waived in such cases.

5. It is usually advisable that all the poles in a given lead be owned by the same utility rather than that the ownership be mixed (except of course under *joint ownership*). Provision for this is desirable, also for the general proportion of the total number of poles to be owned by each party.

6. Provision should be made for abrogation of existing agreements or bringing them into agreement with the joint-use contract. Also it should be stipulated how third parties may be allowed on the poles if necessary.

7. The details of application for and issuance of permits for the use of any pole should be specified, also what the permit covers, what is considered an attachment, etc.

8. Provision for maintenance of poles and lines should be included. It is customary for each utility to maintain its own lines but the cost of maintenance on poles, especially maintenance such as when poles are broken by storm, is sometimes divided between the two parties.

9. The termination of joint use of any pole is a possibility which must be considered. The owner of the pole should retain the right to recover sole use of his pole if he wishes it, giving the lessee reasonable consideration as to time of removal and relocation of his line. The lessee also should have the right to abandon a joint pole if he wishes, but the owner should have some consideration for the extra cost he may have incurred in preparing the pole for such use. (This may be accomplished by a minimum rental period.) Disposal of the pole (by sale or otherwise) should be provided for in case the owner wished to abandon a pole which the lessee desires to retain.

10. Obtaining of right-of-way, franchises, permits, etc., should be considered.

11. Details of record files, maps, etc., and marking poles in the field should be included.

12. Rental charges (or division of cost in case of joint poles) should be definitely agreed upon. It is customary to set up a

standard joint pole of certain size and class (such as 35-ft. Class B or Class C pole) and the rental based on an equitable division (one-half to each party for example) of the annual charges on the cost of such a pole in place, including cost of pole, labor, and a percentage for overhead. Where either party desires a larger pole than the standard, some adjustment of charges is usually made. It will sometimes be found, however, that where the extra-sized poles are comparatively few, the bookkeeping involved in keeping special record of them costs a considerable part of the extra rental received. It is simpler and cheaper in such cases to include a consideration of the higher poles in the single rental charge, making it the same for all poles.

13. Provision should be made for periodic revision of rental charges and also for revision of contract provisions if such changes become advisable.

14. Limitation of the voltage of supply lines is sometimes included in the agreement but such limitation is undesirable from the point of view of the power supply company. Provision should be included however, for methods of discontinuing joint use in case the supply circuits are changed in such a way that the communication utility does not consider joint use any longer possible.

15. Arbitration of points of disagreement is generally provided for.

16. Liability of each party in case of injury to workmen or the public is often covered. Where liability is clearly stipulated by state law however, a clause in the joint-use agreement may be superfluous.

17. The type of construction to be used should be indicated. It is usually convenient to make construction specifications a separate document, referring to it in the main contract. Provision may then be made for greater flexibility in the specifications, revising them or adding to them as frequently as necessary Where no other codes or rules govern, the National Electrical Safety Code is a good reference as the basis of joint construction. It should be kept in mind, however, that the Safety Code is a code of requirements which are considered as minimums for safe-working conditions and is not in any sense a construction specification. Some details of construction requirements will be taken up further.

Construction Requirements.—The Safety Code specifies a definite grade of construction for jointly occupied poles, the

grade depending on the voltage of the supply circuits. This was indicated in Chap. XVI. In general the grades are:

0 to 750 volts	Grade N
750 to 5,000 volts	Grade C
5,000 to 7,500 volts	Grade B
Exceeding 7,500 volts	Grade A
Constant-current circuits, 0 to 7 5 amp	Grade C
7 5 to 10 amp	Grade B
Exceeding 10 amp	Grade A

NOTE.—If the *supply* circuit is in cable, Grade C applies in most cases Where the communication circuit may be classed as a minor circuit (not clearly defined in Code) when the conditions above call for Grade A, Grade B may be used, and when they call for Grade B, Grade C may be used The requirements are somewhat less for communication circuits used only in the operation of supply circuits.

The requirements for the different grades are indicated in various points in previous chapters in discussing strength of different parts of the construction.

The clearances prescribed by the Safety Code are discussed in Chap. XXIII. In general it is recommended that the supply circuits be placed above the communication circuits. The vertical separation should be as follows:

Between supply circuits, 0 to 7,500 volts, and communication circuits	48 in.
Between supply circuits, 7,500 to 50,000 volts, and communication circuits	72 in.
Between non-current carrying parts of supply equipment (such as transformer cases) for 0 to 7,500 volts, and communication circuits	40 in.
Between non-current carrying parts of supply equipment (such as transformer cases) for 7,500 to 50,000 volts, and communication circuits	60 in.
Between non-current carrying parts of supply equipment and communication equipment	same as above for corresponding voltage
Between supply circuits 0 to 750 volts or in cable at any voltage and non-current carrying parts of communication equipment	40 in
Between span wires or brackets for lamp or trolley contact conductors and cross-arms carrying communication conductors	24 in.
messenger wires carrying communication cables	12 in.
terminal boxes of communication cables	12 in.

In the specifications it is well to indicate the maximum load which may be carried on the *standard pole* and on other larger poles. For example, the following might be given in heavy-loading districts:

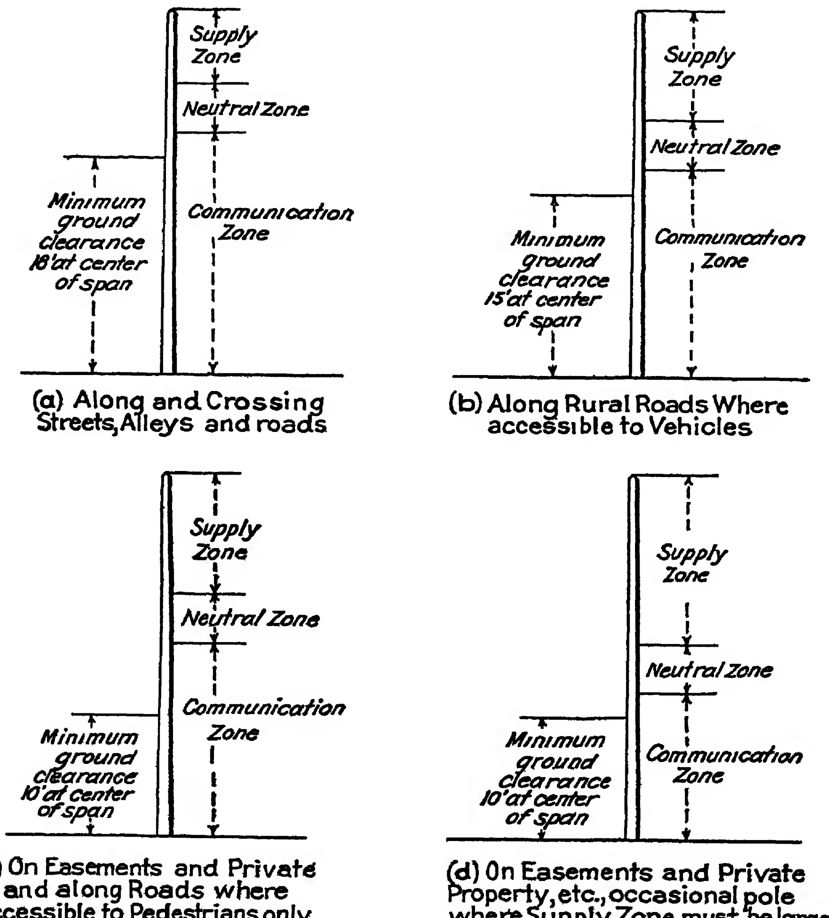


FIG. 338.—Allotment of pole space, based on ground clearance.

MAXIMUM LOAD ON 35-FT. CLASS C POLE, IN SPANS NOT OVER 150 FT.

8 power wires not larger than No. 2 (T.B.W.P.)
1 telephone cable not larger than 200 pair
1 twisted pair telephone wire

The side-wind pressure on various conductors was given in Chap. XXII. Table XLVII gives a few of the ordinary sizes

of wire and several sizes of telephone cable, the loading being that of 8 lb. per sq. ft. wind on the wires covered with ½ in. of ice. Strength of poles was discussed in Chap. XVI.

TABLE XLVII — WIND LOADING ON ICE-COVERED WIRES

		Pounds per Foot
No. 6 T.B.W.P		0 88
No. 4 T.B.W.P.		0 92
No. 2 T.B W.P.		0 96
No. 0 T.B.W.P		1 08
No 0000 T B W.P		1 19
50-pair cable (including messenger)	24 gauge	2 04
	22 gauge	2.06
200-pair cable (including messenger)	24 gauge	2 45
	22 gauge	2 53
600-pair cable (including messenger)	24 gauge	3 05
	22 gauge	3 08

The spacing of poles should be carefully specified with due regard to the allowable loading and the spans allowable for each type of circuit. Spans over 150 ft. are usually not advisable.

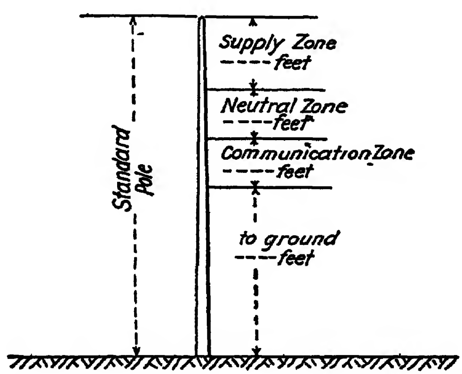


FIG. 339.—Allotment of pole space, on standard pole.

The space allotted to each utility on a pole should be definitely indicated. Conditions will usually vary, the required clearance above ground being different in an easement than along a street, for example. The space assignment is quite often governed by the height above ground which is required by the communication circuits and attachments. It is sometimes feasible therefore

to indicate the division of pole space for various conditions as shown in Fig. 338, on the assumption that the communication line will take such space as is necessary; the supply lines taking what is left above the required neutral zone in each case, making

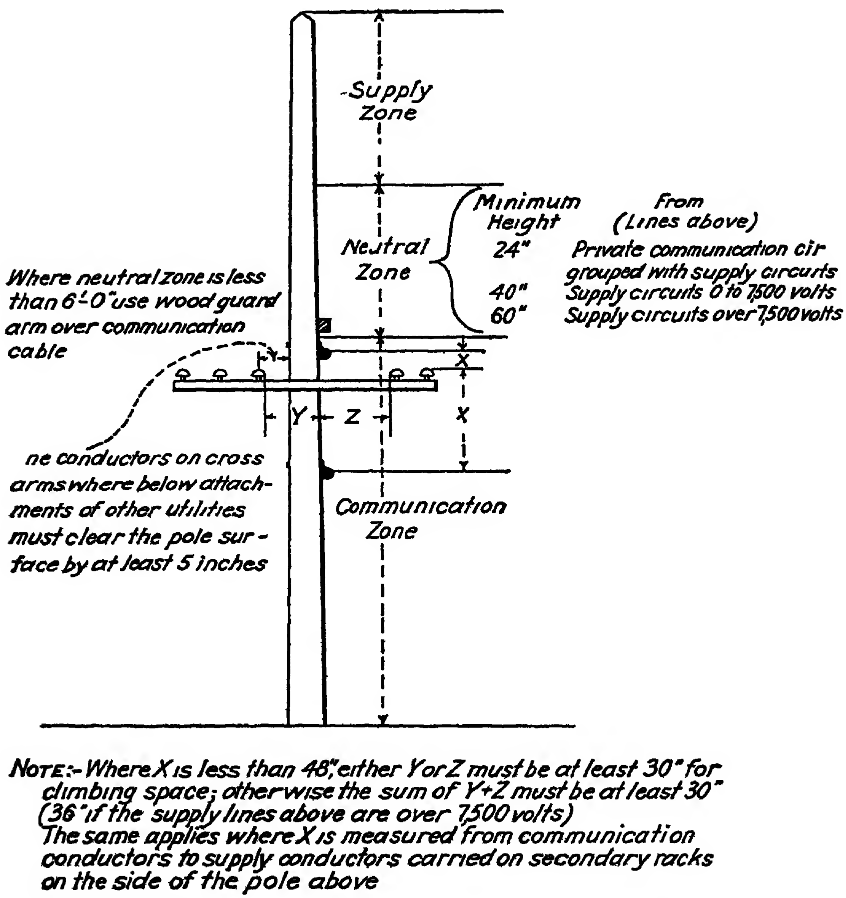


FIG. 340.—Neutral space, climbing space, etc.

their construction conform with the space allowed. Another method which is based on a *standard division* of a *standard pole* is shown in Fig. 339. It is perhaps seemingly more equitable but does not make for as great economy as the first method indicated, since ground clearance, and hence the necessary communi-

cation zone, is not the same for all locations. If more space than the standard is required by the supply zone, a higher pole must be set unless the communication zone can be decreased. Some intermediate method between the two indicated is also possible.

The amount of space required for the neutral zone is indicated in the clearances given above and is shown graphically in Fig.

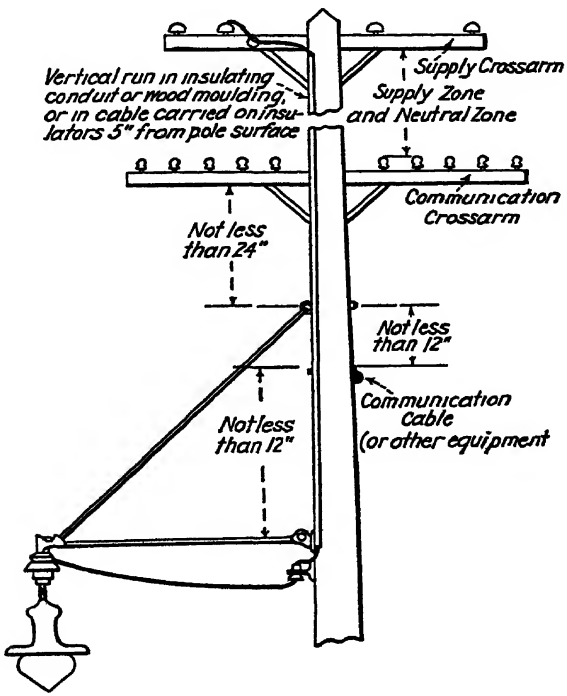


Fig. 341.—Clearances with street-lamp fixture.

340. Climbing space requirements are also shown on the same figure. A guard arm must be used over the telephone cable where the neutral zone is less than 6 ft. high. If it is assumed that this arm is for the protection of linemen working on the supply circuits as well as protection of the cable, it should be required that no attachments be placed on that arm, otherwise a hazard may be introduced.

The clearance with a street lamp mounted on the pole is indicated in Fig. 341.

In Fig. 342 is shown the method of making vertical runs down the pole, Fig. 342(*a*) showing the protective covering for cables, Fig. 342(*b*) for ground connection wires, and Fig. 342(*c*) a service cable (750 volts or less) on insulators.

The above points are indicative of some of the features which should be covered in the specifications. Some engineers prefer

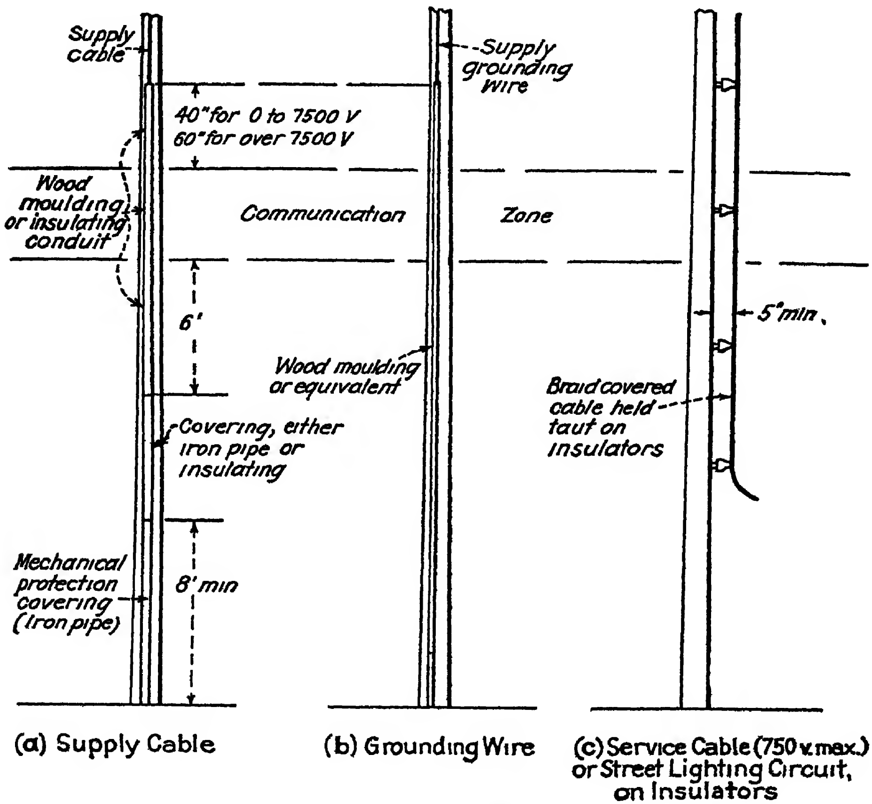


FIG. 342.—Vertical runs

to make the specifications complete, covering all the requirements for the construction of the lines of both utilities, and not depending upon the Safety Code or other rules for reference. Where the Safety Code or other similar rules govern the construction of both companies, however, it is essential only that such points as are not clearly covered in the code or rules, and need explanation or amplification, such points as are not covered or not sufficiently covered and on which special agreement has been reached

between the two companies, and such parts as refer specifically to the joint use of the poles, need be covered by these specifications,

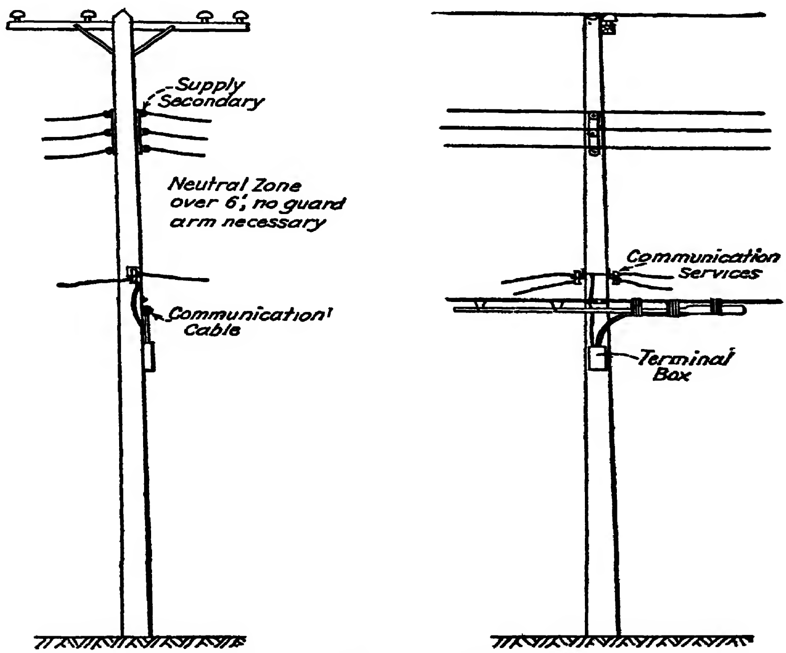


FIG. 343.—Typical joint use construction.

assuming that the construction of each utility otherwise will be in conformance with the code or other governing rules.

Figure 343 shows a typical pole construction with joint use.

CHAPTER XXX

FUNDAMENTAL THEORY

The material in this chapter is included as a source of ready reference for some of the major points of fundamental theory in connection with the mechanical design of distribution lines. The usual conceptions of stresses and strains in materials are given and the action of ordinary types of beams, columns, etc., under load. It is not intended to be in any way a complete discussion of the various subjects but more as a reminder of the considerations involved and the formulæ used, it being assumed that the reader already has a working knowledge of the theory of stresses and strains in materials and structures.

Stress.—Whenever a body is subjected to external forces, there is a resulting tendency within the body for the molecules to become displaced or the body to become disrupted. The internal force which resists this tendency is called "stress." The term is also somewhat loosely applied to the external force as well, and for ordinary purposes no confusion results from such use.

The term "strain" is also sometimes used in referring to the externally applied forces but strain in reality refers to the distortion of the material due to its being stressed and hence should not be used to designate applied force or loading.

Stresses due to mechanical forces are, in general, of three kinds:

1. *Tensile stress* or tension is the stress which tends to keep the adjoining planes of a body from being pulled apart under the influence of the forces acting away from each other, Fig. 344(*a*).

2. *Compressive stress* or compression is the stress which tends to keep two adjoining planes of a body from being pushed together under the influence of two forces acting toward each other, Fig. 344(*b*).

3. *Shearing stress* or shear is the stress which tends to keep two adjoining planes of a body from sliding one on the other under the influence of two forces, parallel and in opposite directions, Fig. 344(*c*).

A body under tension or compression has present in it shearing stresses also (and vice versa, a body under shear has tensile or compressive stresses). For example, in Fig. 344(*d*), the force P may be divided into two components, P_1 and P_2 along and at right angles to the plane *a-a* which is inclined to the axis of P. P_1 is a tensile stress, P_2 a shear.

Unit stress in a body is the stress which acts on a unit area. If the stress is uniformly distributed over the plane under consideration, unit stress is equal to the total force divided by the area of the plane. Unit stress is expressed in pounds per square inch, tons per square foot, kilograms per square centimeter, etc.

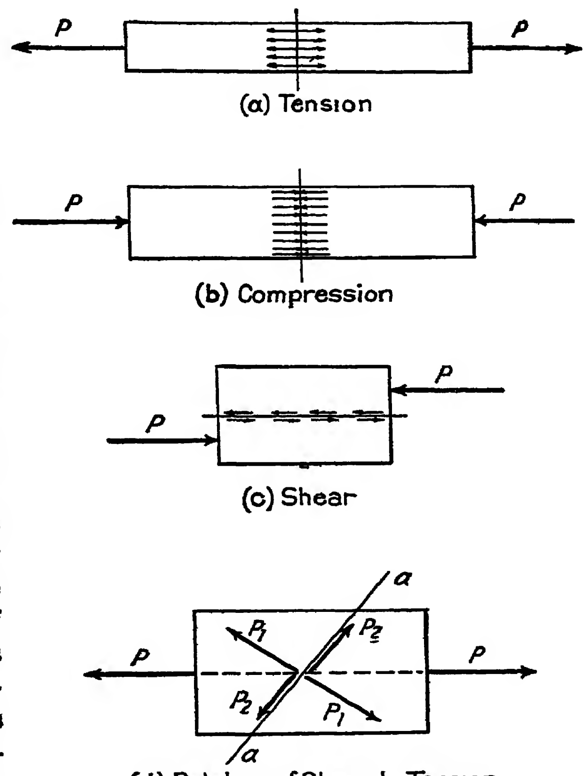


FIG. 344.—Simple stress.

Elasticity.—When a body is stressed, some deformation results, as no material is perfectly inelastic although there are various degrees of elasticity in various materials. The deformation (sometimes called strain as explained above) may be (*a*) elongation due to tension, (*b*) shortening due to compression, (*c*) slipping of one plane on another due to shear.

When the stress does not exceed a certain limit, which is different for different materials, the deformation will be practically proportional to the stress. If the stress is applied and then removed, the body will return to its original size. After that limit has been reached, if the stress is increased, the deformation will be relatively greater in proportion to the stress, and if the

stress is then removed, the body will not regain its original size but will have a certain amount of permanent deformation or *set.* If the stress is increased still further, a point will eventually be reached at which no further increase can be made. Either the body becomes disrupted or fails at that point, or deformation continues without further increase in stress until failure occurs.

Figure 345 illustrates a typical stress-deformation curve. Up to the point A, the stress is directly proportional to the deformation and the curve is a straight line. The point A is called the *true elastic limit.* Beyond A the deformation increases more

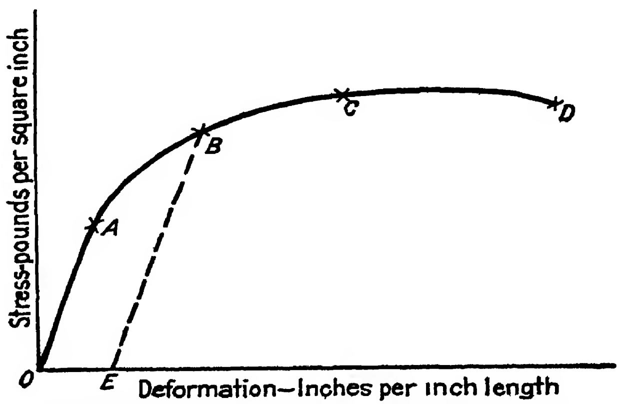


FIG. 345.—Typical stress-deformation curve.

rapidly than the stress and, if the stress were released at some point such as B, the relation of stress and deformation would follow some such line as BE, back to zero stress, and the body would have a permanent deformation equal to OE. At the point C no further appreciable amount of stress can be added. For ductile materials, such as steel, the body may continue to deform without increase in stress and with perhaps a final decrease in stress until failure finally takes place at D. Non-ductile materials usually will not show the latter phenomena, failing at C. The point C is called the *yield point. Ultimate strength* is the maximum stress reached, at C or possibly a little higher. The *strength at rupture* may be lower than the ultimate as indicated at D.

Different materials differ widely in the shape of their elastic curves. For steel, for example, the point A is relatively high, stress being proportional to deformation for a fairly high percentage of ultimate strength. For soft-drawn copper, on the

other hand, the portion OA of the curve is relatively short, there being some permanent deformation at comparatively low stress.

The *elastic limit* as defined above is likely to be lower than it is practicable to use in design, especially with such materials as soft-drawn copper. A higher practicable value is obtained, called "*Johnson's elastic limit*" after J. B. Johnson who suggested it, by assuming the elastic limit as the point on the elastic curve where the tangent has a slope 50 per cent greater than the slope of the lower straight part of the curve (up to the true elastic limit). Another suggested elastic limit uses a point whose slope is twice that up to the true elastic limit. The *yield point* is sometimes used as the elastic limit, but this is undesirable.

The slope of the straight part of the curve, up to the true elastic limit, is called the "*modulus of elasticity.*" It is commonly designated by the symbol E and is expressed by

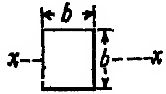
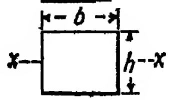
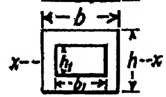
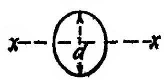
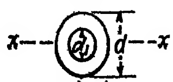
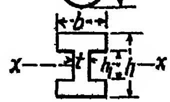
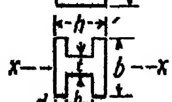
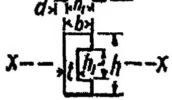
$$E = \frac{\text{unit stress (pounds per square inch)}}{\text{unit deformation (inches per inch)}}.$$

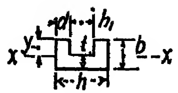
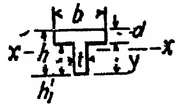
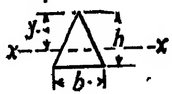
A design must be based on some specific unit stress which is considered *allowable* or *working stress.* The relation between the ultimate strength of the material and this working stress is called *safety factor.* A safety factor is necessary to allow for the following considerations, in designing a structure which will be safe: (*a*) the material may vary in quality, some being weaker than the average strength assumed; (*b*) the loads may be more at some times than is foreseen in the design (this is especially true in structures subject to impact loading); (*c*) the elastic limit may be of the order of 50 per cent of the ultimate strength and it is desirable to avoid permanent deformation in a structure by not exceeding the elastic limit.

The size of the safety factor to be used depends on the degree with which the above considerations affect the problem. For distribution-line design, the loads to which the structures are assumed to be subjected are usually an extreme condition which will seldom, if ever, be reached. The safety factors used may be somewhat less, therefore, than is required for other structures where the assumed maximum loading is more often experienced.

Moments of Inertia.—The moment of inertia of plane areas enters into many of the computations of stresses in bodies. The moment of inertia of an area about some line or axis is equal to

TABLE XLVIII.—PROPERTIES OF COMMON SECTIONS

	Distance neutral axis to extreme fiber (y)	Moment of inertia about neutral axis (I)	Section modulus I/y	Radius of gyration
	$\frac{1}{2}b$	$\frac{1}{12}b^4$	$\frac{1}{6}b^3$	$\frac{b}{\sqrt{12}} = 0.0289b$
	$\frac{1}{2}h$	$\frac{1}{12}bh^3$	$\frac{1}{6}bh^2$	$\frac{h}{\sqrt{12}} = 0.0289h$
	$\frac{1}{2}h$	$\frac{1}{12}(bh^3 - b_1h_1^3)$	$\frac{bh^3 - b_1h_1^3}{6h}$	$\sqrt{\frac{bh^3 - b_1h_1^3}{12(bh - b_1h_1)}}$
	$\frac{1}{2}d$	$\frac{\pi d^4}{64} = 0.0491d^4$	$\frac{\pi d^3}{32} = 0.0982d^3$	$\frac{d}{4}$
	$\frac{1}{2}d$	$\frac{\pi(d^4 - d_1^4)}{64} = 0.0491(d^4 - d_1^4)$	$\frac{\pi(d^4 - d_1^4)}{32d} = 0.0982\frac{(d^4 - d_1^4)}{d}$	$\frac{\sqrt{d^2 + d_1^2}}{4}$
	$\frac{1}{2}h$	$\frac{bh^3 - h_1^3(b - t)}{12}$	$\frac{bh^3 - h_1^3(b - t)}{6h}$	$\sqrt{\frac{bh^3 - h_1^3(b - t)}{12[bh - h_1(b - t)]}}$
	$\frac{1}{2}b$	$\frac{2db^3 + h_1t^3}{12}$	$\frac{2db^3 + h_1t^3}{6b}$	$\sqrt{\frac{2db^3 + h_1t^3}{12[bh - h_1(b - t)]}}$
	$\frac{1}{2}h$	$\frac{bh^3 - h_1^3(b - t)}{12}$	$\frac{bh^3 - h_1^3(b - t)}{6h}$	$\sqrt{\frac{bh^3 - h_1^3(b - t)}{12[bh - h_1(b - t)]}}$

	$y = \dfrac{b^2h - h_1(b-t)^2}{2[bh - h_1(b-t)]}$	$\dfrac{h_1t}{12}\left[t^2 + 12\left(b - y - \dfrac{t}{2}\right)^2\right] + \dfrac{db}{6}[b^2 + 3(2y - b)^2]$	$\dfrac{I}{y}$	$\sqrt{\dfrac{I}{A}}$
	$y = \dfrac{bh^2 - h_1^2(b-t)}{2[bh - h_1(b-t)]}$	$\dfrac{bd}{12}\left[d^2 + 12\left(h - y - \dfrac{d}{2}\right)^2\right] + \dfrac{th_1}{12}\left[h_1^2 + 12\left(y - \dfrac{h_1}{2}\right)^2\right]$	$\dfrac{I}{y}$	$\sqrt{\dfrac{I}{A}}$
	$y = \frac{2}{3}h$	$\frac{1}{36}bh^3$	$\dfrac{bh^2}{24}$	$\dfrac{h}{\sqrt{18}} = 0\ 0236h$

the sum of the products obtained by multiplying each infinitesimal area of the cross-section by the square of its distance from the axis, see Fig. 346.

$$\text{Moment of inertia} = I = \Sigma z^2 da. \tag{105}$$

The moment of inertia cannot be obtained by any simple computation but requires a process of integration. Table XLVIII gives the moments of inertia for various ordinary sections.

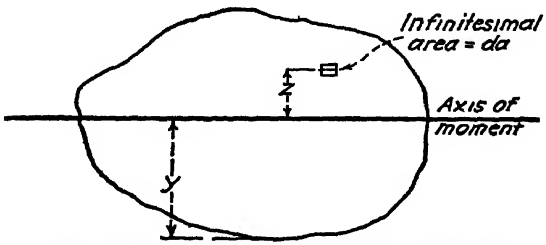


FIG. 346.—Moment of inertia—general.

The axis about which moments of inertia are usually figured for the purpose of stress computations is one through the center of gravity of the section. This is called the *neutral axis* of the section in this case since, under bending stress, the stress is zero along this axis (see below). The axis used in Table XLVIII is the neutral axis.

It is sometimes desirable to find the moment of inertia about some other axis than the one for which the moment may be known. For example, from Table XLVIII the moment of inertia of a rectangle about its neutral axis is $\frac{1}{12}bh^3$. The moment of inertia about an axis along one edge of the rectangle, but parallel to the neutral axis may be desired, see Fig. 347. It may be determined by adding to the moment of inertia about the first axis (neutral) the area of the rectangle times the square of the distance from the first axis to the second. For the case of the rectangle assumed above, the moment of inertia about axis a-a is

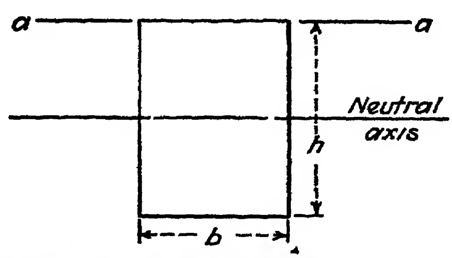


FIG. 347.—Transfer of axes—moment of inertia.

$$I_{a-a} = \frac{1}{12}bh^3 + bh\left(\frac{h}{2}\right)^2 = bh^3\left(\frac{1}{12} + \frac{1}{4}\right) = \frac{1}{3}bh^3.$$

This relation holds true for any other area as well as the rectangle used in the example. It is useful in computing the

moment of inertia of odd-shaped sections such as T or channel sections which can be subdivided into rectangular or triangular parts. The moments of each of these parts can be figured about its own axis and then transferred to the neutral axis of the section as has been indicated.

A moment of inertia about an axis perpendicular to the plane of the section is sometimes used. This is called the "*polar moment of inertia.*" This moment of inertia is similar to the moment defined above except that the distance Z in the formula $I = \Sigma z^2 da$ is the distance from a point in the plane rather than from a line, see Fig. 348. The polar moment of inertia may be obtained from the moments of inertia given above (about an axis in the plane of the section). It is equal to the sum of the moments of inertia about two axes at right angles to each other through whose intersection the polar axis passes—axes a-a and b-b, Fig. 348. For example, the moment of inertia of a circular area about its neutral axis is $0.0491d^4$. The polar moment of inertia about a polar axis through the center of the circle would be

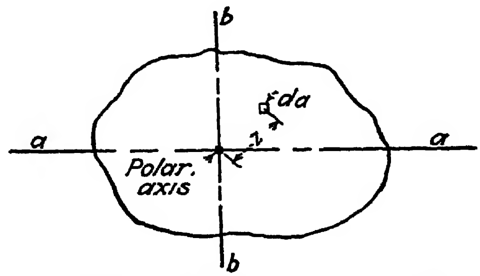


FIG. 348.—Polar moment of inertia.

$$J = 2I = 0.0982d^4. \tag{106}$$

This polar moment of inertia is used in computing torsional stresses.

Another quantity which is used in the computation of stresses in columns is the *radius of gyration* of the cross-section. The radius of gyration may be defined as the equivalent distance from the axis at which the whole area of the section might be concentrated in order to give the same moment of inertia about that axis as it gives in its distributed form.

$$\text{Radius of gyration} = r = \sqrt{\frac{I}{A}}, \text{ where } A = \text{area of section.}$$

The quantity *section modulus* is sometimes used in computing stresses in beams. The section modulus is equal to the moment of inertia of the section about its neutral axis (I) divided by the

distance from the neutral axis to the extreme edge of the section (farthest edge, if edge is unsymmetrical).

$$\text{Section modulus} = \frac{I}{y} \text{ (Fig. 346).}$$

Bodies under Tension.—The usual case of a body acted on by a force which puts it in tension is when the tension is axial and may be considered as uniformly distributed over the area—the tension in an overhead conductor for example or in a guy wire. The unit stress is simply figured in this case, Fig 349.

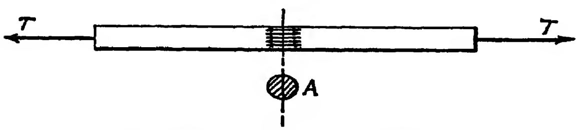


FIG. 349—Body in tension

$$f = \frac{T}{A}, \tag{107}$$

where

f = unit stress in pounds per square inch.
T = total applied force in pounds.
A = cross-sectional area in square inches.

Bodies under Compression—Columns.—Where compressive force is applied to a body of uniform cross-section in such a way

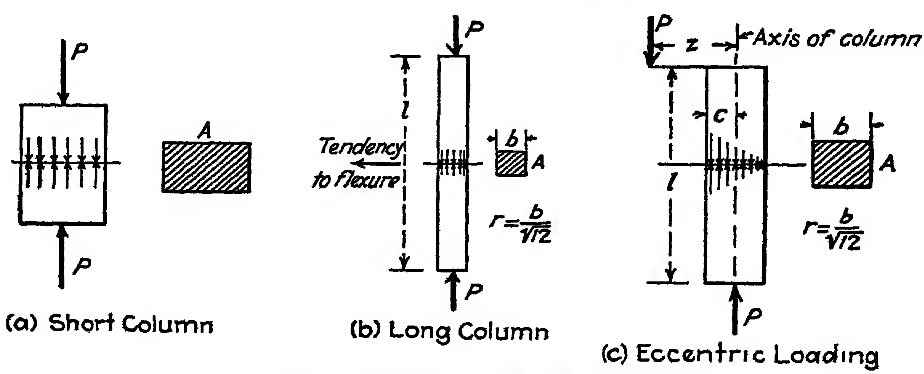


FIG. 350.—Compressive stress in a body.

that it is symmetrical to the axis of the body, the compressive stress may be considered as uniformly distributed over the cross-section and, if the body is fairly thick in comparison to its length (such as a short column), the unit stress is (Fig. 350 (*a*)),

$$f = \frac{P}{A}, \tag{108}$$

where

$$P = \text{total applied force in pounds.}$$

Where the body is long between points of lateral support, it is subject to flexural stresses which tend to make it buckle (Fig. 350 (*b*)). Hence, the unit stress cannot be figured by the above formula; it would be too small. Several formulæ are used which take account of this factor of slenderness. The simplest is probably the "straight-line formula" which is of the form

$$\frac{P}{A} = S - \frac{Cl}{r}, \tag{109}$$

where

S = the unit stress at the ultimate in compression.
C = a constant determined by experiment, and depends on the material, and the conditions of the ends of the columns.
l = the unsupported length.
r = the minimum radius of gyration of the cross-section.

Ultimate strength constants are given in the "American Civil Engineers' Handbook" as follows:

TABLE XLIX.—ULTIMATE STRENGTH CONSTANTS FOR THE STRAIGHT-LINE COLUMN FORMULA

$$\frac{P}{A} = S - \frac{Cl}{r}$$

Material and end condition	S	C	Limit of l/r
Structural steel:			
Round ends	35,000	150	160
Fixed ends	35,000	75	320
One end round, one fixed	35,000	100	240
Cast iron:			
Round ends	34,000[1]	175	90
Fixed ends	34,000[1]	88	160
One end round, one fixed	34,000[1]	116	115
Wood:			
Round ends	5,000[1]	75	75
Fixed ends	5,000[1]	37	150
One end round, one fixed	5,000[1]	50	112

[1] This is less than the ultimate in compression for small specimens of cast iron or wood, but from tests of full-size columns seems to be the value to be used for full-size castings or

A similar formula for computing the strength of poles as columns is given in the National Electric Light Association's "Overhead Systems Reference Book" as

$$\text{Ultimate strength} = f\left(1 - \frac{L}{60D}\right), \qquad (110)$$

where

f = the ultimate strength of the material in tension in pounds per square inch.

L = the total length of the column in inches.

D = the least dimension (diameter) of the pole in inches.

The ratio l/r in the formula given above is a measure of the slenderness of the column and is called the "*slenderness ratio.*"

Where the load on the column is not applied along its axis but at some distance from the axis it is called an "*eccentric load*" and the stress in the column will not be uniform across its cross-section. The straight-line formula given above may be modified as follows to give the maximum unit stress in the column, *i.e.*, the stress in the side nearest the load.

If S = the maximum unit stress,

c = distance from axis of column to side of greatest stress,

Z = distance of load from axis of column,

$$\frac{P}{A}\left(1 + \frac{cZ}{r^2}\right) = S - \frac{Cl}{r}, \text{ see Fig. 350}(c). \qquad (111)$$

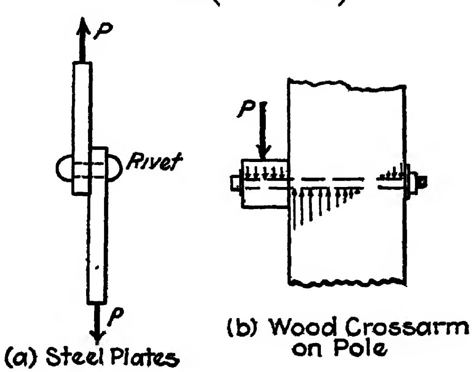


FIG. 351.—Simple shear.

An example of eccentric loading is the weight of a transformer hung on the side of a wood pole.

Bodies under Shear.—A simple example of shearing stress is the case of two steel plates, held together by bolts or rivets, and being pulled in opposite directions (Fig. 351 (*a*)). The total force P acting on one plate must be transferred to the other plate through the rivet (neglecting friction between plates). At the plane where the plates meet, the rivet is acted on by a force P in one direction tending to slide the part of the rivet on one side of that plane past the part on the other side of that plane which

is acted upon by a force P in the opposite direction. The shearing stress in the rivet along that plane is, therefore,

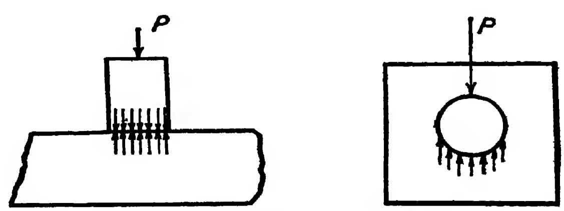
$$f = \frac{P}{A}, \tag{112}$$

where

A = the cross-sectional area.

Another example is the shearing stress in the steel bolt with which a wood cross-arm is attached to a wood pole. Here, however, the situation is somewhat complicated by the fact that the wood is relatively soft compared with the steel and some deformation of the arrangement is likely to occur, due to the wood crushing slightly, long before the shearing stress in the bolt is anywhere near its ultimate strength. Such deformation will produce tensile stresses in the bolt (other than those accompanying the shearing stress).

Bearing.—Another form of stress is illustrated by Fig. 352. Where load is transferred from one body to another, the transfer takes place along the plane on which they meet. The tendency



(a) Flat Bearing Surface (b) Curved Bearing Surface

FIG. 352.—Bearing.

is for the material to give way or crush under the load, producing a *bearing stress* in the material. Where the stress is uniformly distributed over the area the unit stress is

$$f = \frac{P}{A}, \tag{113}$$

where

A = the area of contact (projected area in case of curved surfaces such as bolts).

The stress f should not exceed the allowable bearing strength of the material.

An example of bearing stress is the bearing of the plates on the rivet in Fig. 351 (*a*) and of the bolt on the cross-arms and the pole, Fig. 351 (*b*). In the case of the pole, the bearing cannot be considered as uniformly distributed along the length of the bolt but is probably more as indicated by the arrows in Fig. 351 (*b*). The maximum bearing stress would therefore be somewhere in the neighborhood of $4\frac{P}{ld}$,

where

l = length of bolt in the pole.
d = diameter of bolt.

Bending Stress—Beams.—When a body is held or supported at one or more points and forces are applied at other points in such a way as to tend to cause flexure or bending in the body, tension, compression, and shear are all set up in the body. The tensile and compressive stresses at any section are functions of the moment of forces on either side of the section about that section. The shearing stress is a function of the sum of the forces on either side of the section.

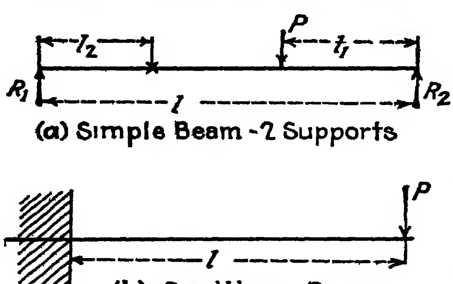


FIG. 353.—Simple beams.

The *moment* of a force about any point is the product of the amount of that force and the shortest distance (perpendicular) from its line of direction to that point. In a beam the moment of any force acting upon it about any cross-section of the beam is equal to the product of the force and its distance from the section.

There are two axiomatic rules in connection with the forces on a beam:

(*a*) The algebraic sum of *all* the forces acting on a beam must be equal to zero.

(*b*) The algebraic sum of *all* of the moments of forces about any point or section of the beam must be equal to zero.

Assume the simple beam with two supports and one concentrated load shown in Fig. 353 (*a*).

Under rule (*a*), the sum of the reactions at the supports, $R_1 + R_2$, must be equal to P.

Under rule (*b*), the sum of the moments of all the forces about either support, such as R_2, must equal zero.

$$R_1 l - P l_1 + R_2 0 = 0$$

$$R_1 = \frac{l_1}{l} P. \tag{114}$$

$$R_2 = P - R_1 = P\left(1 - \frac{l_1}{l}\right). \tag{115}$$

The amount of the *reactions at the supports* are thus determined.

In the case of the simple cantilever beam, Fig 353 (*b*), the moment of the load P about the fixed end, *i.e.*, Pl, is counteracted by a moment within the support.

The *bending moment at any section* for which the stress is to be computed is found by taking the moments of all the forces on either side of the section. The moments for the forces on one side will be the same as for those on the other side, since the body is in equilibrium. For example, in Fig 353 (*a*), take the section at x, at a distance l_2 from the left-hand support.

The moment about x,

$$M_x = R_1 l_2, \text{ on the left hand side,} \tag{116}$$

also

$$M_x = -R_2(l - l_2) + P(l - l_1 - l_2) \quad \text{on the right hand side.} \tag{117}$$

It may be seen by comparing these with the values of R_1 and R_2, given above, that the two values of M_x are equal (but of opposite sign since the same direction of rotation was assumed as positive in both cases).

The *shear at any section* is found by taking the algebraic sum of all the forces on either side of the section. From Fig. 353 (*a*), the shear at the section x

$$\begin{aligned} \text{Shear}_x &= R_1 \text{ on the left-hand side} \\ &= R_2 - P \text{ on the right-hand side} \end{aligned}$$

which values are also equal and of opposite sign.

In Fig. 354 are shown diagrams representing the shears and bending moments along several simple types of beams. Figure 354 (*a*) is for a beam with concentrated loads and two supports, Fig. 354 (*b*) for a similar beam with uniformly distributed load

of w lb. per foot, Fig. 354 (c) for a cantilever beam with concentrated load at the end, and Fig. 354 (d) for a cantilever beam with uniformly distributed load.

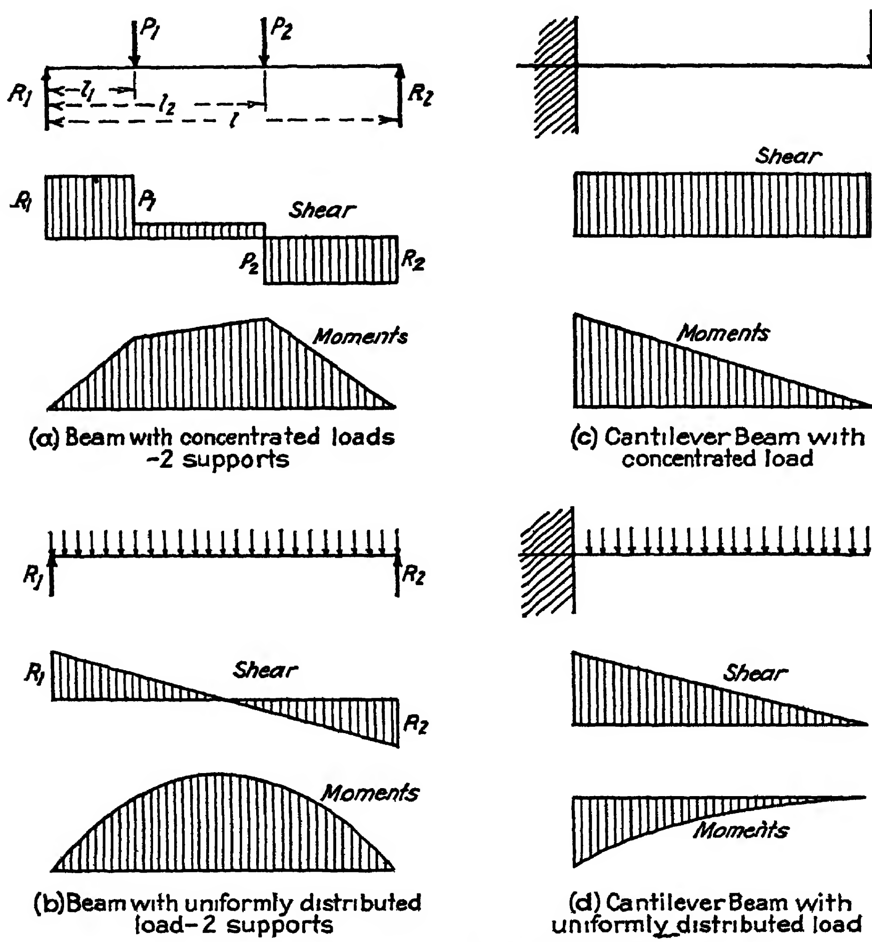
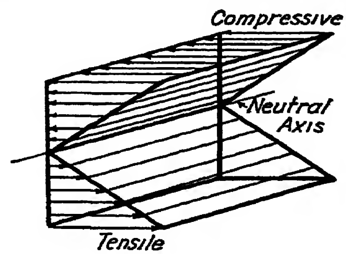


FIG. 354.—Shear and bending moment diagrams.

The maximum bending moment in any case will be at the point where the shear is zero; that is, where the shear changes from positive to negative or *vice versa.* In a cantilever beam that point will be at the support.

The bending moment at any section, for equilibrium, must be balanced by a moment of stresses or *resisting moments* in the

interior of the material. The beam is deflected somewhat and on one side the material is in compression and on the other side in tension. On the side in compression the material is shortened proportionally, on the side in tension it is lengthened The stress is distributed across the section as shown in Fig. 355. At the extreme edges of the section (top and bottom) the unit stress is evidently a maximum, decreasing from there to zero at an intermediate *neutral* point. Considering the cross-section as an area, the neutral point becomes a line, or a neutral axis, Fig. 355 (*b*). For a symmetrical cross-section, such as a rectangle or a circle, the neutral axis lies midway between the extreme edges



(a) Typical Distribution

(b) Representation of Total Distribution

FIG. 355.—Distribution of stress across section of beam.

and maximum unit tensile stress is equal to maximum unit compressive stress. For unsymmetrical sections, such as a **T**, the neutral axis lies nearer the one side than it does the other. In such a case, the maximum stress occurs on the side farthest from the neutral axis. The neutral axis in any case passes through the center of gravity of the cross-section.

Since the stress on any infinitesimal area of the section is proportional to its distance from the neutral axis, from Fig. 355(*b*), if

y = the distance from neutral axis to extreme edge of section,
f = unit stress at the extreme edge,
z = the distance of any infinitesimal area from the neutral axis,

$$\text{stress on infinitesimal area} = S = \frac{z}{y} f da.$$

$$\text{Total resisting moment} = \sum Szda = \sum \frac{f}{y} z^2 da.$$

$$\Sigma\, z^2 da = \text{moment of inertia of the section} = I.$$

$$\therefore \text{resisting moment} = M' = \frac{fI}{y}.$$

The resisting moment is equal to the bending moment, hence

$$\text{bending moment} = M = \frac{fI}{y}, \tag{118}$$

where

f = maximum unit stress on extreme fiber of section.
y = distance of extreme fiber from neutral axis.
I = moment of inertia of the cross-section about the neutral axis.
$\frac{I}{y}$ = section modulus of the section.

The *shear* on any cross-section of the beam is resisted by the internal shearing stress in the beam. The average shearing stress will be

$$f_s' = \frac{\text{shear}}{A}.$$

The shearing stress is not uniformly distributed, however, the maximum shearing stress being

$$f_s = K\frac{\text{shear}}{A}, \text{ at the neutral axis,} \tag{119}$$

where K is a constant depending on the shape of the section.

K = 1.50 for a rectangle
= 1 33 for a triangle
= 1.33 for a circle
= 2.5 approximately for steel I beams, etc.

The horizontal shearing stress at any point is equal to the vertical shearing stress. Wooden beams which are somewhat weak in horizontal shear, often fail by shear along their central or neutral plane.

The *deflection of* a beam at any point is obtained by integration of the expression,

$$M = EI\frac{d^2y}{dx^2},$$

assuming the origin of coordinates at a point where the slope of the elastic curve is zero, y being the deflection at a point x distance from the origin. Maximum deflections for various beams are given in Table L.

Continuous beams or beams with more than two supports cannot be figured as simply as a beam with two supports since the

bending moment at intermediate supports is not zero. The general equations for solving such beams are as follows, see Fig. 356(*a*): Let

M', M'', M''' be the moments at three consecutive supports
w' the uniform loading per foot in the first span whose length is l'.
w'' the uniform loading per foot in the second span whose length is l''.

Then

$$M'l' + 2M''(l' + l'') + M'''l'' = -\tfrac{1}{4}w'l'^3 - \tfrac{1}{4}w''l''^3. \quad (120)$$

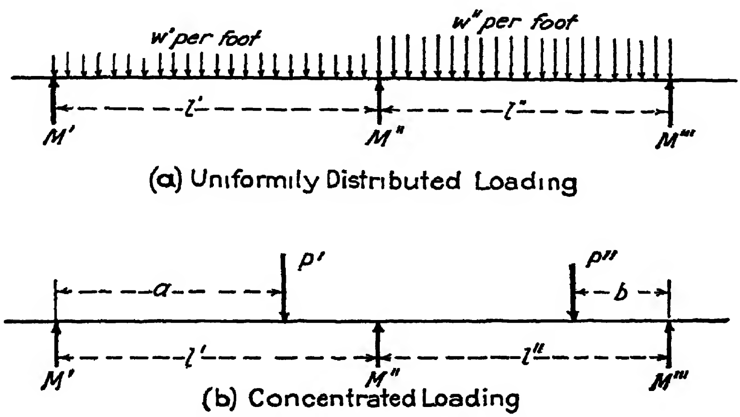


FIG. 356.—Continuous beams.

Enough of these equations are written for groups of three consecutive supports to allow the solution to be made by simultaneous equations. For a three-support beam, the moments at end supports being zero (M' and $M''' = 0$), the equation becomes,

$$2M''(l' + l'') = -\tfrac{1}{4}(w'l'^3 + w''l''^3). \quad (121)$$

If $l' = l''$ and $w' = w''$ the general equation becomes,

$$M' + 4M'' + M''' = -\tfrac{1}{2}wl^2. \quad (122)$$

and for three-support beams,

$$4M'' = -\tfrac{1}{2}wl^2$$
$$M'' = -\tfrac{1}{8}wl^2. \quad (123)$$

From the values of the moments, the reactions of the supports may be computed.

For *concentrated loads*, the general formula is, see Fig 356(*b*),

$$M'l' + 2M''(l' + l'') + M'''l'' = -\frac{P'a(l'^2 - a^2)}{l'} - \frac{P''b(l''^2 - b^2)}{l''}. \qquad (124)$$

Which reduces, if P' and P'' are equal and midway between supports and $l' = l''$, to

$$M' + 4M'' + M''' = -\tfrac{3}{4}Pl. \qquad (125)$$

For beams with uniform loading, w per foot and spans of equal length (l), the reactions are as follows:

Three-support beam.. ..	$0.375wl$	$1.25wl$	$0.375wl$	
Four-support beam . ..	$0.4wl$	$1.1wl$	$1.1wl$	$0\ 4wl$

For beams with concentrated loads P placed midway between supports, with spans of equal length l the reactions are as follows:

Three-support beam.......	$0\ 3125P$	$1.375P$	$0.3125P$	
Four-support beam........	$0.35P$	$1.65P$	$1.65P$	$0.35P$.

Table L gives some of the quantities discussed above, for several of the more common types of beams.

Torsion.—Torsional or twisting forces applied to a body are resisted by shearing stresses in the body. The total resisting moment at any plane is equal to the sum of the products of the unit stress on each infinitesimal area times the distance of that area from the axis of the body. If the maximum unit stress f_s occurs at a distance y from the axis (the extreme edge of the section), the unit stress on any given area da will be

$$f_s'' = \frac{z}{y}f_s.$$

$$\text{The total resisting moment} = \sum\frac{z^2}{y}f_s da$$

$$\Sigma z^2 da = \text{the polar moment of inertia} = J.$$

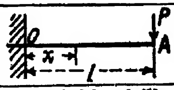
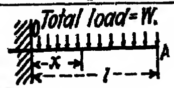
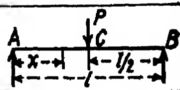
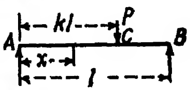
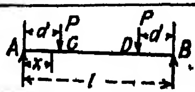
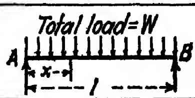
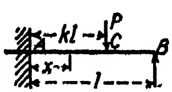
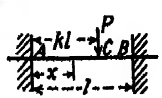
Hence,

$$\text{resisting moment to torsion} = \frac{Jf_s}{y},$$

and

$$\text{torsional moment} = Pe = \frac{Jf_s}{y}, \qquad (126)$$

TABLE L.—CHARACTERISTICS OF SIMPLE BEAMS

Beam	End reactions	Shear at any section	Moment at any section	Maximum moment	Maxium deflection
		$V = P$(constant)	$M = -P(l - x)$	$M = -Pl$ at O	$y = -\frac{Pl^3}{3EI}$ at A
		$V = W - \frac{Wx}{l}$	$M = -W\left(\frac{l}{2} - x - \frac{x^2}{2l}\right)$	$M = -\frac{Wl}{2}$ at O	$y = -\frac{Wl^3}{8EI}$ at A
	$R_A = R_B = \frac{P}{2}$	$V = \pm\frac{P}{2}$	$M = \frac{Px}{2}$ for A-C	$M = \frac{Pl}{4}$ at C	$y = -\frac{Pl^3}{48EI}$ at mid-span
	$R_A = P(1 - k)$ $R_B = Pk$	$V = P(1 - k)$ for A-C $V = -Pk$ for C-B	$M = P(1 - k)x$ for A-C $M = Pk(l - x)$ for C-B	$M = Pkl(1 - k)$ at C	$y = -\frac{Pl^3}{3EI}(1 - k)$ $\times (\tfrac{2}{3}k - \tfrac{1}{3}k^2)^{3/2}$ at $x = l\sqrt{\tfrac{2}{3}k - \tfrac{1}{3}k^2}$
	$R_A = R_B = P$	$V = P$ for A-C $V = 0$ for C-D $V = -P$ for D-B	$M = Px$ for A-C $M = Pd$ for C-D $M = P(l - x)$ for D-B	$M = Pd$ at any section C to D	$y = -\frac{Pd}{24EI}(4d^2 - 3l^2)$ at mid-span
	$R_A = R_B = \frac{W}{2}$	$V = \frac{W}{2} - \frac{Wx}{l}$	$M = \frac{Wx}{2} - \frac{Wx^2}{2l}$	$M = \frac{Wl}{8}$ at mid-span	$y = -\frac{5}{384}\frac{Wl^3}{EI}$ at mid-span
	$R_B = \frac{P}{2}(3k^2 - k^3)$	$V = \frac{P}{2}(2 - 3k^2 + k^3)$ for A-C $V = \frac{P}{2}(3k^2 - k^3)$ for C-D	$M = \frac{P}{2}[x(2 - 3k^2 + k^3)$ $- l(2k - 3k^2 + k^3)]$ for A-C $M = -\frac{P}{2}[x(3k^2 - k^3)$ $+ l(k^3 - 3k^2)]$ for C-B	$M_A = -\frac{Pl}{2}(2k - 3k^2 + k^3)$ $M_C = \frac{Pl}{2}(3k^2 - 4k^3 + k^4)$	
		$V = P(1 - 3k^2 + 2k^3)$ for A-C $V = -Pk^2(3 - 2k)$ for C-B	$M = P[(1 - 3k^2 + 2k^3)x$ $- l(k - 2k^2 + k^3)]$ for A-C $M = P[(2k^3 - 3k^2)x$ $+ (2k^2 - k^3)l]$ for C-B	$M_A = -Plk(1 - 2k + k^2)$ $M_B = -Plk^2(1 - k)$ $M_C = Plk^2(2 - 4k + 2k^2)$	

where

P = force applied.

e = distance from point of application to axis of body.

Impact Loading.—Moving loads striking a body produce greater stresses than the same loads applied statically. In the case of a beam, the beam is deflected in resisting the impact. It is often difficult to estimate just what impact loads will be encountered in practice and their effect may be allowed for somewhat in the safety factor used. For a falling load P on a beam the resulting maximum stress is given by the formula

$$f_i = f + f\left(l + \frac{2h}{d}\right)^{1/2}, \tag{127}$$

where

h = the height from which it falls,

d = the deflection which would be produced by the same load statically applied,

f = the maximum stress due to the same load statically applied.

For a horizontally moving force,

$$f_i = f\left(\frac{2h}{d}\right)^{1/2}. \tag{128}$$

Combined Stresses.—Bodies are sometimes subject to two kinds of forces simultaneously, one producing flexure and the other either compression or tension. An example is a wood pole which supports the weight of wires, transformers, etc., acting as a column in compression, and also supports horizontal wind loading acting as a cantilever beam. For practical purposes the maximum stress on the compression side of the column may be obtained by adding the stress computed as a beam

$$f_1 = \frac{My}{I}$$

to that computed as a column

$$f_2 = \frac{P}{A}.$$

$$f = f_1 + f_2.$$

On the tension side,

$$f = f_2 - f_1.$$

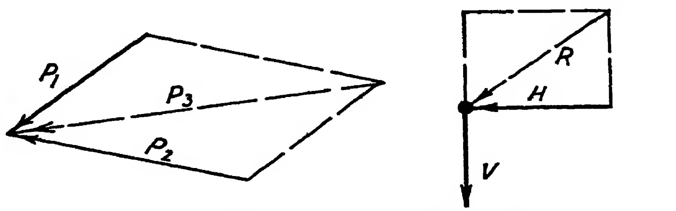
Temperature Effect.—Bodies expand as their temperature increases. The measure of this expansion is known as the "coeffi-

cient of linear expansion" and is the percentage by which a body is increased in length for each degree rise in temperature. If

l_0 = initial length at temperature t_0,
l_1 = length after a rise in temperature to t_1 degrees,
α = coefficient of linear expansion,

$$l_1 = l_0[1 + \alpha(t_1 - t_0)]. \tag{129}$$

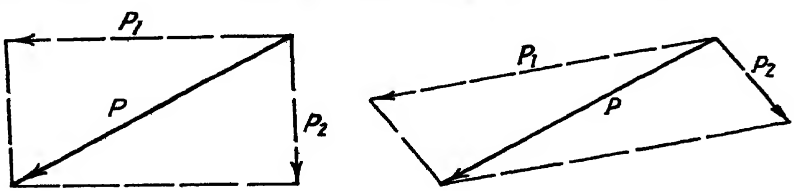
Resolution and Composition of Forces.—When two or more forces act on a body at the same point, a single equivalent force may be determined by addition of the forces. If they have the



(a) Sum of P_1 and P_2 (b) Forces acting on a loaded wire

FIG. 357.—Composition of forces

same line of action, the addition may be direct; if different, vector composition may be used. Let two forces P_1 and P_2 be represented in magnitude, direction, and sense by vectors as shown in Fig. 357(a). They may be added to give the equivalent force P_3.



(a) Resolution of P into P_1 and P_2 at right angles to each other (b) Resolution of P into P_1 and P_2 not at right angles to each other

FIG. 358.—Resolution of forces.

An example of the above is the combination of forces acting on a loaded wire, the vertical force being the weight of wire and its ice loading and the horizontal force being the wind pressure. The resultant force is obtained as shown in Fig. 357(b).

As the converse of the above, a force may be resolved into two components acting in different directions. In Fig. 358 let P

be a given force. It may be resolved into two components at right angles to each other, of magnitude, direction, and sense, P_1 and P_2. An example of such a resolution is when the tension in a guy wire attached to a pole at a dead end is resolved into two components, P_1 horizontal, opposing the tension in the line wires, and P_2 vertical which acts on the pole, putting it in compression.

More than two forces may be treated in a similar manner.

PART III
ECONOMICAL DESIGN

CHAPTER XXXI

ECONOMICAL DESIGN

"Economical design" as applied to a distribution system deals primarily with a study of costs. The fundamental principle of economical design is *the determination of a system or part of a system whereby energy may be transmitted to the customer at the least possible cost consistent with good service.* In the above definition the two chief phrases should be emphasized separately. These are "least possible cost" and "consistent with good service." The latter phrase is just as important a part of the statement of principle as the first part—perhaps more so—and implies the consideration of a number of more or less intangible factors as will be pointed out.

The application of economical design to the distribution system opens a large and important field for study. It was pointed out in Chap. I what a comparatively large proportion of the total system investment was found in the distribution system. The economy of generation has had intensive study and has been brought to a point where it is hard to see how, with the present methods of generation, many further major economies can be realized. The distribution system, however, is a field which has had, in general, comparatively little attention from this viewpoint. It is here that considerable savings may be effected with properly directed study.

Economic design in this connection, should be viewed in its broader sense and not as a mere striving to save a few dollars of investment here and there. It is true that one of its chief objects is the investigation and presentation of the costs involved when alternative means are possible by which a desired result may be accomplished. However, it does not follow that its purpose ends there, in recommending for adoption the alternative which is cheapest in dollars and cents. There are many other factors which affect a great many of the problems encountered. Some of these are

The state of finances of the company.

The general financial situation—the ease of obtaining money at that particular time.

Company policy in its relations with the public—whether or not it believes in spending money freely to improve service and to maintain the appearance of its property.

Sightliness of the structures involved in the problem.

Local regulations (governmental, etc.).

Economical design of the system as a whole, as affected by the particular part under consideration.

Possible future developments in the art and also in loads carried.

Reliability of the design—possible troubles which may appear.

Quality of service which is demanded or desirable to render.

All these factors and other similar considerations must be included in the qualifying clause in the statement of principle in the first paragraph above—*consistent with good service.* The best economic design may point to the alternative which is cheapest in first cost, or it may indicate the one which has the least annual cost, or it may, on account of some of the other factors involved, select some other alternative whose cost is by no means the lowest. Economical design, therefore, should not be considered as merely the determination of the cheapest condition, but rather as the obtaining of the best *economic* solution, taking into account all factors involved including, as well as tangible costs, the more intangible elements indicated above. In such a study, the application of *good judgment* is a prime essential. Especially is this true in dealing with the intangible elements mentioned. Good judgment is quite largely a matter of experience. It can be applied more intelligently however, as the number of unknown factors in a problem are reduced. If the relative costs of several alternative designs are known, the particular advantages of any one over another in other regards can be weighed against the difference in cost.

Good service, referring specifically to the quality of electrical service rendered the customer, is a matter which requires some definition for any specific case. It will vary considerably under different conditions. Ideal service, of course, would be such that there would be no interruptions and that the voltage regulation would be within narrow limits under all circumstances, with the supply adequate for any demand. This subject was discussed somewhat in Chap. III and elsewhere and the points brought out need not be repeated here. It is sufficient to point out that service requirements are not so strict for certain classes of load as they are for others, and the practicability of rendering service of a high degree of continuity and regulation depends somewhat

on the location, density of load, etc. In general, the better the service, usually, the greater the cost. It is probable that quality of service to all classes of load is improving on most systems as better engineering is applied to the distribution system, and customers are learning to expect better service. These factors must be taken into account in any study of distribution design. Other considerations which must not be lost sight of are the beneficial effects of good quality of service on public relations and the fact that sometimes the customers would prefer adequate service, even at an increase in price, to inferior service at a low rate. In any case, the quality of service should be decided upon and then the design made as economical as possible and still render that service. The chief business of the power company is furnishing "good service" and economical design should naturally be secondary to that.

The relation of "economical design" to "electrical design" and "mechanical design" has been previously pointed out to some extent in Chaps. II and XV. Electrical design calls for a knowledge of electrical phenomena and the application of this knowledge to the achievement of results which will be satisfactory from an operating standpoint. In other words, the solution for any problem must be one that will meet its requirements. There may be more than one solution which meets this condition, however. Mechanical design calls for a study of materials used and their combination into the desired structures in such a way that proper factors of safety are obtained. Economical design requires a knowledge of costs and their application to the determination of the most economical design possible within the limitations imposed by the other types of design and the considerations mentioned in previous paragraphs. It is evident that there must be overlapping between these three fields. Both electrical and mechanical design should be planned with a view toward economy. Where there is a choice of more than one alternative which is satisfactory from the electrical and mechanical standpoints, the decision should be based on a study of the relative economy of all alternatives considered.

All engineering should make for efficiency. There cannot be real efficiency, however, unless economy is also considered. Efficiency in its limited sense refers to the reduction in losses—an efficient machine is one whose output is as nearly as possible equal to the input. Reduction in losses may usually be attained

by an increase in investment and it must not be lost sight of that the increase in investment may well be greater than the gain accomplished in reducing losses. Efficiency in the broader sense takes into consideration the cost of reducing losses and the most truly efficient design will be one in which the losses are only as low as is consistent with economy.

It is rather difficult to show tangible results of economical design on the distribution system. The system is so widespread, the loads carried are often so diversified and so variable, both as to demand and to consumption from day to day and from year to year, and are metered at so many different points, that any very definite exhibit of actual results accomplished is well-nigh impossible. They should be evident, it is true, in the final analysis of yearly investment costs and operating costs for the system, but even here there are so many other contributing factors that it is difficult to state confidently that any particular effects are the results of economies on the distribution system. For it may be found that real economy lies in increasing the investment to decrease the losses or, conversely, an increase in losses may effect a greater economy in investment. It can often only be asked that the economies which can be exhibited be accepted as representative of others fully as large which can only be computed; that the percentage of economy which can be figured for the small individual job be considered to apply similarly to the large general class of similar jobs. A few examples are given below which indicate the results which may be obtained by economical design. They are taken from studies made under certain actual (and not unusual) conditions of load, voltage, etc., and were based on costs determined as accurately as possible at the time the studies were made. While they are not to be considered of general application, they are at least indicative of the magnitude of what may be discovered by a study of other similar conditions. Methods of making such studies will be taken up in later chapters.

1. Primary Lines.—Figure 359 shows a comparison of the total annual costs per 1,000 ft. of line for various sizes of wire under various loads on a 4,600 volt, three-phase power line. The most economical size for any load is apparent. What it is wished to bring out especially is the actual amount in dollars which may be saved by the use of one size of wire rather than another. Take for example a load of 1,000 kw. It might be carried satis-

factorily on No. 2 wire under certain conditions. Number 0000 wire, however, would give an annual cost about $185 less for 1,000 ft. or $555 per year if the line were 3,000 ft. long. A similar comparison may be made between No. 0 and No. 0000 at 1,500 kw.

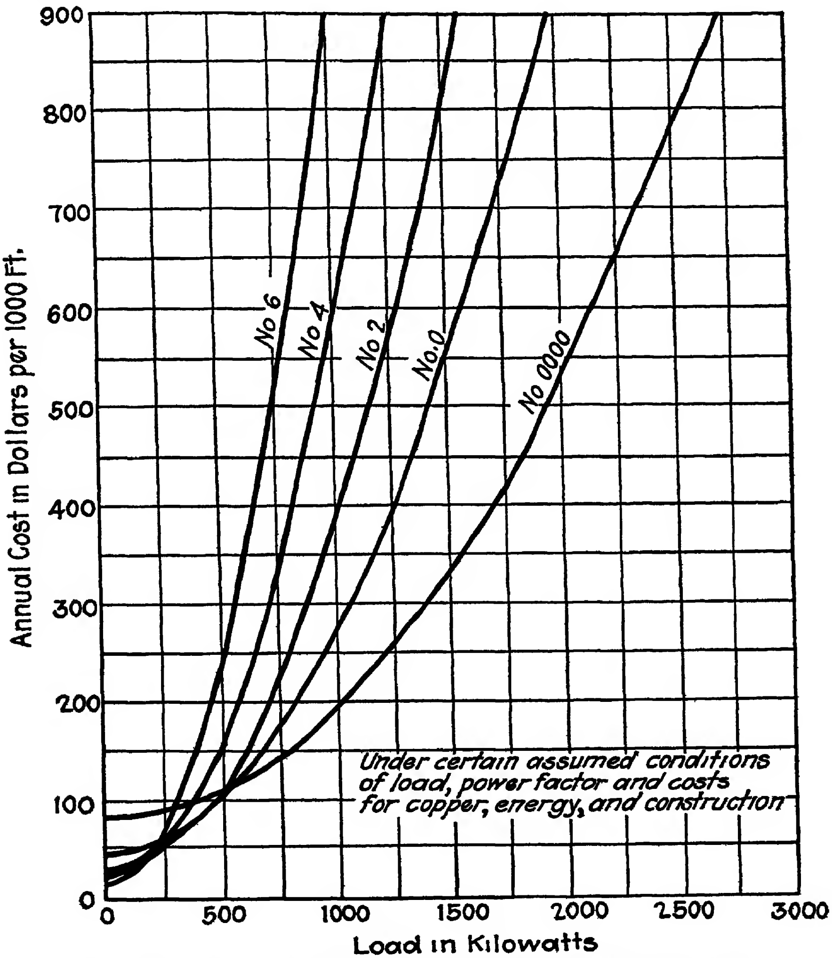


FIG. 359.—Annual cost, 4,600-volt, three-phase power line.

Figure 360 shows the total annual cost of energy losses on two parallel lines, with various divisions of the total load between the two, the total load being 4,000 kw., at a fairly high load factor (about 40 per cent). The natural division of load, if the lines were tied together in parallel would be about 44 per cent to the

No. 0 and 56 per cent to the No. 0000 or a ratio of 0.785. It may be seen that this is not far in cost from the most economical ratio of 0.5 (*i.e.*, one-third the load on No. 0, two-thirds on No. 0000), although there is a difference of $250 per year. If one line only is used, however, and the other held merely as a throw-over, it will be seen that the cost is about $3,000 a year more than for the most economical division. If the load is equally divided (ratio = 1) the excess cost is about $500 per year. It must be recognized, of course, that the most desirable division of such a load is not always practicably possible. However, if the economics are understood the best division possible under the circumstances can be chosen.

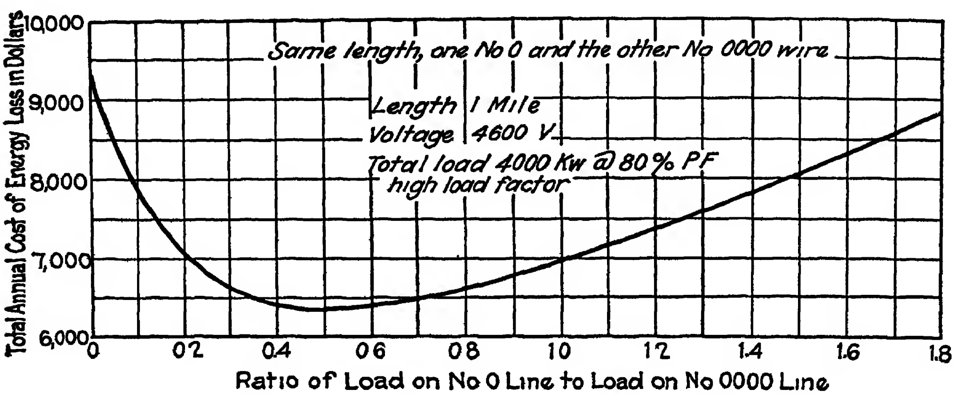


FIG. 360.—Annual cost of energy losses for different divisions of load between two parallel lines.

2. Secondaries.—Figure 361 shows a comparison between the total annual cost per 1,000 ft., including both wire and transformers, for several combinations of wire size and transformer size on single-phase secondary installations under certain conditions, the voltage drop being limited to 3 per cent. For simplicity, only a few of the possible combinations are shown. The others are, for the most part, intermediate in cost to these. It is apparent what the most economical installation for any density of loading is and how much cheaper it is than any other. For example, at 15 kw. per 1,000 ft. the annual cost with No. 6 wire and 15-kv-a. transformers is about $6 per 1,000 ft. less than with No. 4 wire and 10-kv-a. transformers, or No. 2 and 15-kv-a. transformers. It is $22.50 less than with No. 2 wire and 5-kv-a. transformers. The latter might be an unusual condition,

but is not at all impossible, if little consideration is given to the layout of the distribution. These figures are small in themselves but apply to only 15 kw. of load. If the condition is repeated up to a load of 10,000 kw. the possible savings are well worth

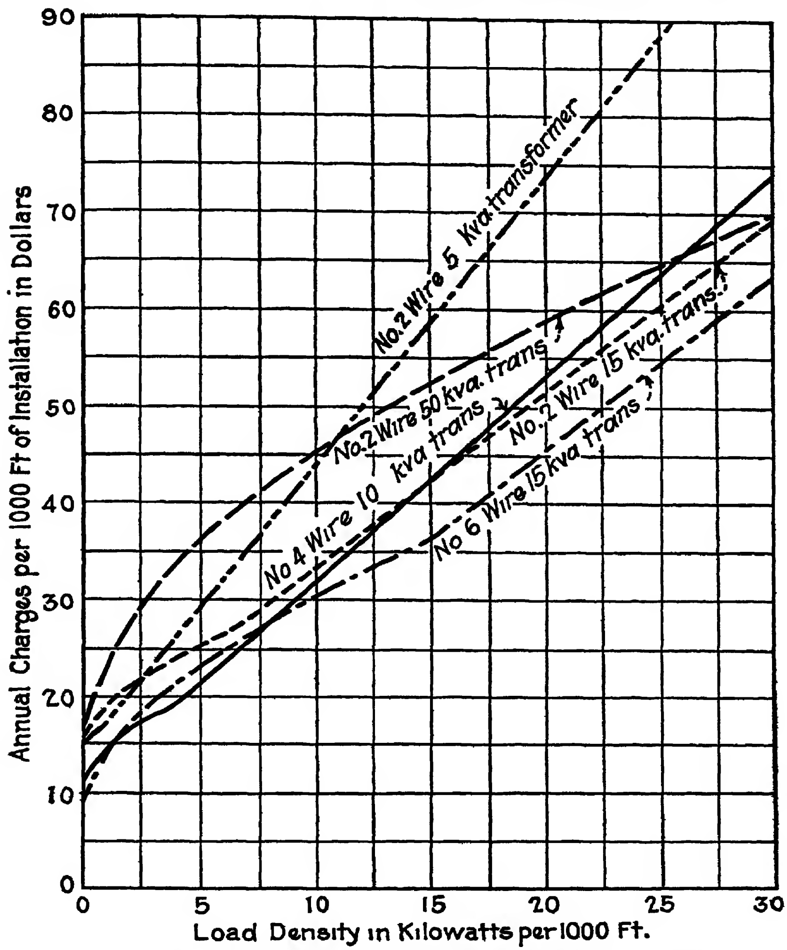


FIG. 361.—Annual cost, single-phase secondary installation. Maximum voltage drop 3%, uniformly distributed load.

while, *i.e.*, from $4,000 to $15,000 per year. The probable future growth of load must be taken into account in this case, of course, and such a size of wire used which will be economical over a long period rather than merely for the present load.

3. Transformers.—Figure 362 shows the total annual charges for various loads on different sized single-phase transformer

installations, under ordinary residence-lighting load and certain other assumed conditions. It is given here to show the monetary value of keeping transformers loaded well up to capacity. Take the 25 kv-a., for example—at full-rated load of 25 kv-a. the annual cost is about $73 or $2.92 per kv-a. At 15-kv-a. load, the annual cost is about $70 or $4.67 per kv-a. That is, at 60 per cent load the transformer cost is $1.75 more per kv-a. per year than at full load. Similarly, with the 15-kv-a. transformer. At

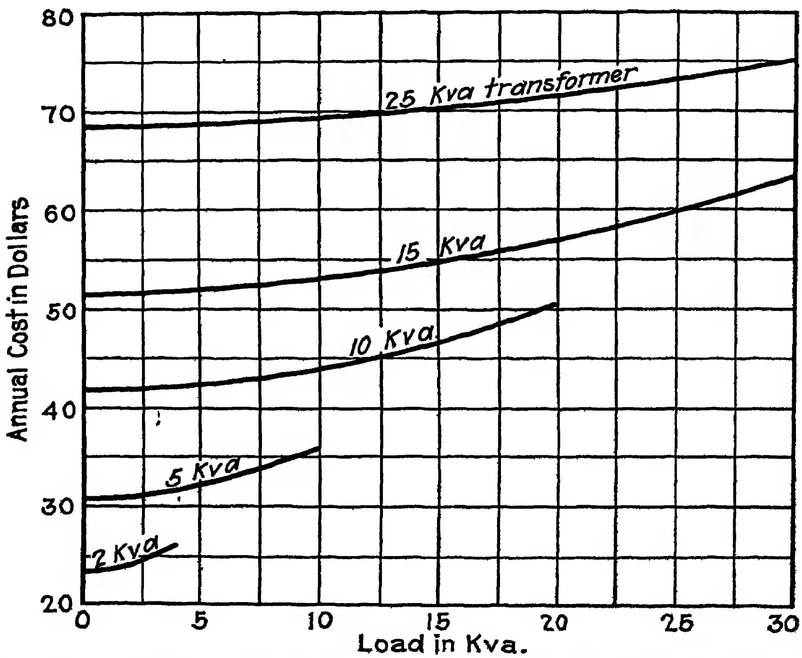


FIG 362.—Total annual cost for single-phase transformer installations.

15-kv-a. load the cost is $3.63 per kv-a. per year. At 60 per cent load (9 kv-a.) the cost is $5.85 per kv-a. per year or an increase of $2.22 per kv-a. If this condition is generally true on a system it may be seen that the excessive cost may be considerable—in the neighborhood of $20,000 per year for a 10,000-kv-a. load for example. It is a generally recognized fact that, with loads of the residence-lighting characteristics, it is safe to load transformers at peak load considerably beyond their rating. Hence it is not at all impossible to keep the transformer loading, on the average, in the vicinity of 100 per cent at least, especially in urban territory. In this connection it is interesting to note

that at 30 per cent overload, for example, a 15-kv-a. transformer costs only \$2 85 per kv-a. per year or about \$0.80 per kv-a. less than at rated load. Also, the greater economy per kv-a. at full load of larger sized transformers over smaller ones is evident, the 25 kv-a. being about \$0.70 cheaper per kv-a. than the 15 kv-a. The choice of transformer size, however, is a problem in which the cost of the secondaries must also be considered, as in Example 2. The only way in which the best transformer economy may be reached is by regular testing and by careful and continued study of loads, increase in loads, transformer spacing, etc. In one actual case (on power loads) by a thorough survey of loads, diversity factors, etc., 35 per cent of the transformer capacity was removed from the lines.

The above are only a few of the examples which might be cited of the economies which may be effected by careful engineering on the distribution system. They show, however, that the magnitude of the results possible is worthy of consideration, when it is remembered that the small savings in the individual case is multiplied many times over the whole system. The same principles may be applied with equal advantage to the choice of voltage, to power-factor improvement, to underground line problems, etc.

The variety of problems which may be studied from the economic viewpoint is almost infinite and the study may be carried to any degree of refinement desired. As a rule, however, extreme refinement is unwarranted. The various factors dealt with are, by nature, exceedingly variable and can best be treated from the standpoint of averages. It would be impracticable in most cases to attempt to consider individually the small everyday problems in design. It is possible, however, to study them as groups or classes and to establish rules and standards which may be quickly referred to in any particular case. It is probable that the most economical solution will not be reached in every case by this method, but on the average, the results will be satisfactory. Major problems can, of course, be dealt with individually and in detail. An important feature of economic study is the training of the judgment of the engineer. If he has a proper conception of fundamental economic relations, his decisions are likely to be much nearer the most desirable solution than they would be otherwise, even though detailed cost studies are not made.

Coming more specifically to the methods of making studies of economical design, it is quite evident that a fundamental requirement is an accurate knowledge of *costs*. These costs include the cost of structures in place, annual charges which should be computed on investment, cost of energy losses, etc These matters will be discussed in succeeding chapters and methods of using them in attacking problems on various divisions of the distribution system will also be indicated. Another requirement for this work, which should be especially noted, is a careful estimate of load carried and load growth. Economy cannot be realized by consideration of present condition only. The situation for some years in the future must be foreseen and allowance made for probable changes in load. A discussion of loads which will be useful in this regard was given in Chap. IV.[1]

[1] The material given here in a book on general distribution engineering must of necessity be somewhat limited. A more complete discussion of the subject may be found in REYNEAU and SEELYE, "Economics of Electrical Distribution."

CHAPTER XXXII

INVESTMENT COSTS

Since economical design is largely a study of costs, it follows that the results achieved will be of value only in proportion to the accuracy of the cost data employed. If basic costs of material, labor, and energy losses are not correctly assumed, the conclusions drawn from their use will be of little worth and may even lead to excessive expenditures. It is usually inadvisable to accept for this purpose any cost data which has been derived for localities or systems other than the one under consideration. Such data may sometimes be convenient for purposes of rough estimates when local figures are not available but they cannot be depended upon as the basis of a final solution. Each company has its own standards of construction, methods of handling labor, standards of wages, efficiencies of operations, etc., and unit costs may differ considerably between different organizations. It is necessary to have as complete and accurate a schedule of local costs as possible as a basis for economic study.

As a rule, in order to get a proper conception of true cost, *annual costs* must be considered rather than the original amount of investment necessary. It is perfectly obvious that, if an article will give twice as long service and costs only 25 per cent more than another similar article, the first article is the cheaper even though it requires a larger initial expenditure. Other factors might have a bearing on the situation which would make it more advisable to use the second article or the one with the smaller first cost, but from the standpoint of cost alone, the first article is preferable—it has the lesser *annual cost.* In some problems where the units being compared are similar, such as two wood poles of different sizes, and the percentage of annual charges would be the same, comparison would usually be based on first cost, but the underlying principle of annual costs is still present, even though not considered directly. Wherever conductors carrying electrical current enter the problem, the use of annual costs is clearly indicated, since the cost of energy losses is a major

factor in the problem, and this is, by nature, an annual cost. The various items which enter annual cost will be taken up in some detail below.

Three kinds of annual costs may be found in any problem: (*a*) Investment costs or annual costs which are proportional to the first cost or initial investment; (*b*) Costs which are constant regardless of the first cost, such as some items of maintenance and operating costs; (*c*) Cost of energy losses. These often bear an inverse ratio to the investment cost.

This chapter will be devoted to investment costs, the cost of energy and energy losses being taken up in Chap. XXXIII. The second class mentioned above—costs which are constant—are of somewhat the same nature as those included as investment costs. In fact, in many problems certain parts of the investment costs are the same for the several alternative designs considered. (The same poles and cross-arms may serve to support quite a range of conductor sizes, for example.) In comparing annual costs of two alternatives, these items cancel each other and drop out of the problem. They must be included however to obtain a complete estimate of cost for any given design.

First Costs.—Before annual costs can be considered, the first cost or initial investment must be determined. This may be a very easy matter in some cases, but there are several factors which are likely to complicate the problem.

The determination of cost figures for general use is greatly facilitated if line construction and methods are standardized (see Chap. XXVIII). Where standards are established, the cost of standard units, such as the cost per pole or the cost per mile of a given type of construction, or the cost per transformer installation, can be set up with a fair degree of accuracy. Otherwise, averages must be assumed which may be quite far from actual conditions in some cases.

Materials.—A complete price list of all materials used is, of course, an essential. This should be kept up to date as prices change, so that at any time the prices used in a problem will represent as nearly as possible the actual cost at that time. When using the price of a material which is subject to any considerable fluctuation, some allowance should be made, however, for the fact that the cost of material on hand in the warehouse may not be represented by the latest quotation, also that future material of the same kind may cost more or less than the

present price. Such future changes may be hard to foretell of course.

In addition to the base cost of the material as represented by vendor's quotations, the cost should include a number of other items. Such things as freight charges from the F.O.B. point to the user's yards, material used in treating poles, tie wires used in tying conductors to their insulators, etc. may be added directly to the quotation for each particular material. Certain other costs are less easily assigned to the individual materials and must usually be determined as a general charge to all materials of a given class and then distributed to the individual material costs by adding to them a percentage to cover their share of the expense. Such costs as these are known as "overhead expense" or "loading." They include such items as:

Waste, end trimmings of wire, cable cut back for splicing, timber cuttings, defective units which cannot be used, and the like.

Loss and breakage, materials lost through carelessness or theft, broken insulators, etc.

Tool expense, tools used up, broken, or stolen, and repairs and other annual charges on investment in tools.

Stores expense, expenses of stores department in handling and warehousing the materials.

Purchasing expense, expenses of purchasing department in purchasing the materials.

The percentage to be used for any given item or class of material will depend largely on local conditions and no figures could be given here which would be of any value. The total percentage for all the items of loading will usually vary from 10 to 35 per cent, depending on the class of property and on local conditions. There is often a question of just how much of a certain expense it is legitimate to consider as proportional to the cost of material. A purchasing department's expense will certainly not fluctuate directly with changes in the prices of materials or even with considerable change in quantities. Stores expense also will not be all directly proportional to material cost. A considerable part of such expenses as these might be considered as coming under the heading of constant costs, and need be included only when a picture of total cost is desired. A considerable amount of good judgment is required in determining the proper amounts to be assigned to loading and the proper distri-

bution of the amounts among the various materials. In some problems which involve only comparatively small amounts of construction, the loading may be safely considered to be equal in any case and comparisons may be made on the basis of actual material and labor costs only. Where good cost records are available, however, it is just as well to include loading in all problems.

Labor.—Unit labor costs are somewhat difficult to determine with any great degree of accuracy, at least costs subdivided in the degree of detail necessary for economic studies. For this purpose, it is sometimes desirable to know, for example, not only how much it costs, on an average, to set a pole but also the difference in the cost of setting different sizes of poles. The usual methods of cost accounting for property-valuation purposes is not likely to give such detailed information. Special methods of studying and obtaining labor costs on various units are usually necessary. Time studies of workmen in the field are probably the best means of getting the data on the smaller units of material. In making such studies it must be remembered, of course, that average costs are desired and allowance must be made for the difference in efficiency of different workmen and the effect of different surrounding conditions on the speed with which work can be done.

Provision may be made for keeping labor costs up to date with any changes which may be made in wage schedules, by the use of formulæ based on man-hours. Otherwise, it is hard to estimate just what the change in the cost has been if different classes of labor at different wages are represented in it. For example, if a wire stringing gang is composed as follows,

1	foreman	(F)
1	driver	(D)
4	linemen	(L)
3	groundmen	(Gr)
1	truck	(T)

the cost per day of that gang may be represented by

$$G = (1F + 1D + 4L + 3Gr + 1T),$$

where the symbols F, D, L, etc., represent the daily cost for the different types of labor indicated. If such a gang can erect, 1½

miles of wire per day, on the average, the cost of erection per mile of wire can be represented by

$$0.667(1F + D + 4L + 3Gr + 1T) = 0.667G.$$

With such a formula, the up-to-date cost can be determined at any time by filling in the formula with present labor prices.

As with material costs, so also with labor costs, there must be included certain additions for *overhead expense* or *loading, i.e.*, such items as:

Unoccupied time, rainy days, vacations, time going to and from the job, time wasted on the job, etc

Transportation, for workmen and for supervisors, engineers and similar employees.

Supervision, heads of departments, general foremen, office expense, clerks, stenographers, etc.

Engineering, expense of engineering force and their office.

Injuries and damages, doctor and hospital expense, liability insurance, and similar costs.

General office expense, expense of departments and officials not directly connected with the work being studied.

The qualifications made in discussing loading of material costs apply equally well here. Some of the above expenses, such as general office expense, are of the nature of constant expenses and cannot be considered as at all proportional to the cost of doing line work. The proportions of the above costs which it is thought proper to include can be totaled and applied to labor costs as a percentage loading. (This will also vary from 10 to 35 per cent, usually.)

Records.—A complete set of cost data for use in making economic studies would, therefore, contain the following:

a. Current prices of material and labor of all kinds used in the work

b. Labor formulæ for various units of construction.

c. Constant multipliers for material and labor costs to care for items (such as tie wires) which are not included separately or in overhead expense

d. Loading percentages for both material and labor costs.

e Current material and labor costs on units of construction, such as a cross-arm, a pole, or an insulator.

f. Current costs on assemblies. The assemblies may range from small units such as a cross-arm erected with its bolts and braces, to a transformer installation, or a mile of line.

A few examples from such a record are shown below by way of illustrations. The figures given must not be assumed to be of general application or representing average current prices since it was pointed out before that cost data can be useful only when derived for the local conditions under which it is to be applied.

a. Prices (at warehouse).

Pole	30 ft. Class C, rough, \$ 7 60, shaved, \$ 9 20 40 ft. Class B, rough, 20 30; shaved, 22 40	
Cross-arm, 96 in., 6-pin	0 82	each
9 in. wooden pin	0 034	each
Primary insulator	0 16	each
Primary fuse box	6 50	each
Weatherproof wire, Nos. 6 to 2...	0.175	per pound

b. Labor Formulæ.

Wire stringing, single wire, gang $= (1F + 1T + 1D + 4L + 3Gr) = G$

	Miles per day	Labor cost per mile	Labor cost + 15 per cent loading
No. 6, T.B.W.P...	2 8	0 3575G	0 4111G
No. 0, bare..	1 8	0 5556G	0 6389G

e. Unit Costs.

	Material	Plus loading	Labor	Plus loading	Total
		18 per cent		16 per cent	
3 No. 4 Secondary, 1,000 ft...	\$94.00	\$110 90	\$31 00	\$36 00	\$146 90
Standard 96 in. light cross-arm.	0 82	1 56	1 00	1 16	2.72
With hardware..	0.50				
		30 per cent		30 per cent	
Pole, 35 ft. Class C	13 85	18.00	6.00	7.80	25 80
40 ft. Class B	22.40	29 10	6.70	8 71	35.80

f. Assemblies.

15 Kv-a Single-phase Transformer Installation
(Material in excess of that normally used on pole)

Material	Price	Plus loading, per cent	Total
1 96-in light cross-arm	$ 0 82	0 22	1 00
1 transformer block	0 45	0 22	0 55
4 flat cross-arm braces	0.39	0 22	0 48
4 angle brackets	0 60	0 22	0 73
1 straight bracket .	0.11	22	0 13
5 primary insulators	0 80	30	1 04
10 ⅜ × 4 in. galvanized machine bolts	0 19	22	0 23
6 ⅜ × 5 in. galvanized machine bolts	0 13	22	0 16
2 ⅝-in. galvanized machine bolts	0 15	22	0 18
2 ½ × 5 in. lags......	0 05	22	0 06
2 ⅜ × 4 in lags ...	0 04	22	0 05
16 ⅜ in. washers . 4 ⅝-in. washers .	0 10	22	0 12
2 square plate washers	0 03	22	0 04
50 feet of ground moulding	1 00	24	1 24
17 pipe straps	0 15	22	0 18
2 ground rods	1 50	24	1 86
3 lightning arresters	18.00	22	22 00
2 secondary fuse holders	2 30	22	2 81
2 secondary fuses.....	0 15	22	0 18
2 primary fuse holders .. .	6 50	22	7 92
2 primary fuses.	2.00	22	2 44
7 lb. weatherproof copper wire	1 23	20	1 48
Total	$36 69		$ 44 88

Labor ⅓$(1F + 1T + 3L + 3Gr)$ = $13.90 +15.5 per cent (loading) . . .	$ 16 10
Total, labor and material	$ 60 98
15-kv-a. single-phase transformer, $145 + 17.0 per cent (loading)	169 80
Total.	$230 78

The above are merely examples selected at random and in no way indicate the entire record. Such a record may be made as complete in the matter of assembly costs as is found useful. A complete set of unit costs (items *a*, *b*, *c*, *d*, and *e*) will be found of great service in any case, however, and, once compiled, is not difficult to keep up to date.

Figure 363 is given as an illustration of the division of costs on poles and wire found in one case by a cost analysis. While not

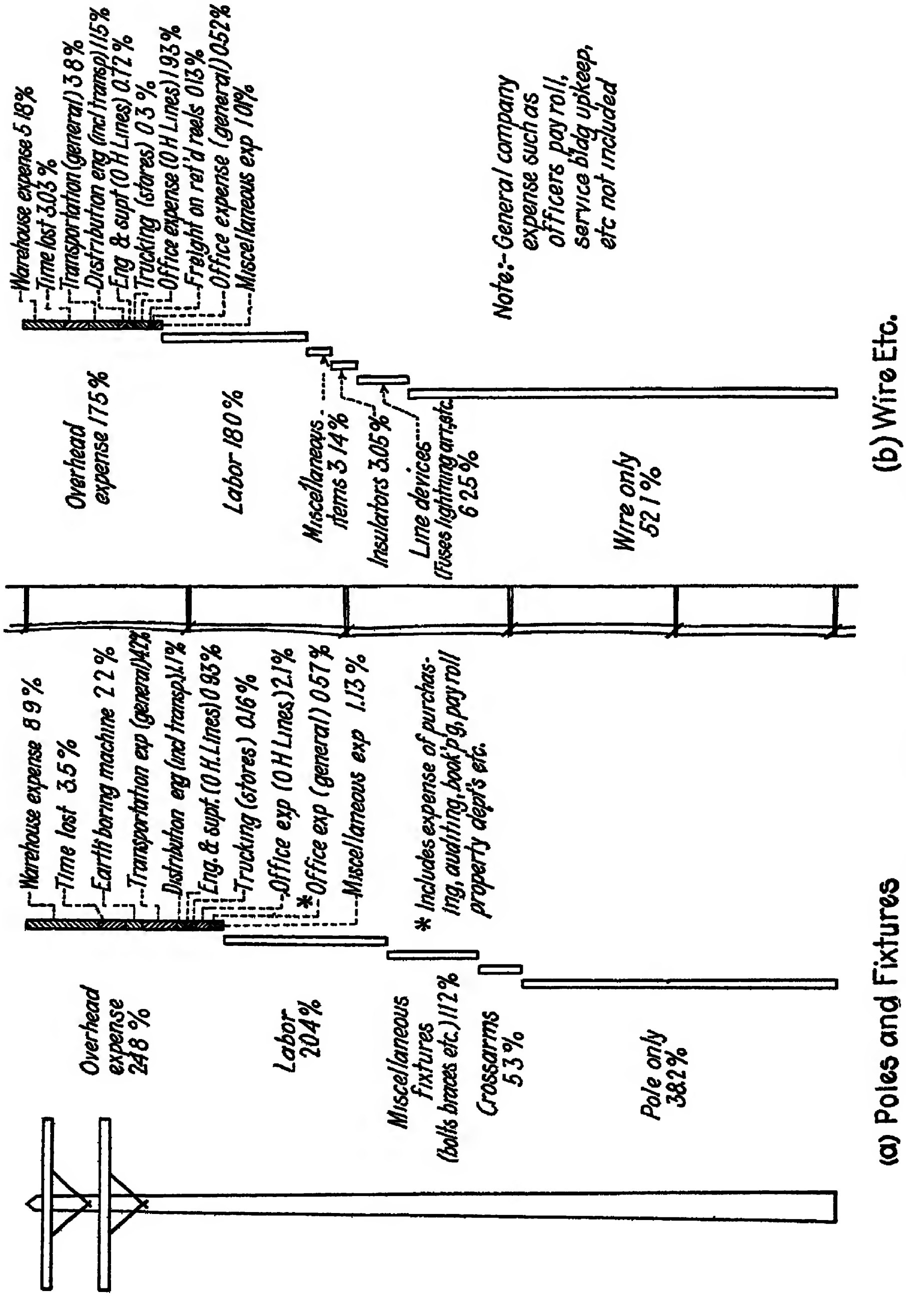


FIG. 363.—Component costs on poles and wire, overhead distribution.

to be considered as of general application, it is interesting to note the proportion of cost assigned to the various items such as labor and overhead expense.

Annual Costs.—Investment costs in any piece of property which is in service for a period of years may be considered as spread over that period in equal annual amounts. The various elements which enter into that annual cost will be discussed in turn.

Interest.—Whenever money is invested in a piece of property a legitimate rate of interest may be expected as part of the earnings of that property. If the money be borrowed money, interest must be paid to the creditor. If it is not borrowed money, it might be put out elsewhere at a legal rate of interest, so a fair return from the property is justified, not as a matter of profit, but as a legitimate repayment of cost.

Interest must be figured on the total investment represented by the structure in place, including material costs, labor costs, and overhead expense.

The rate at which interest should be charged may vary with the problem under consideration. As a rule it should be the current rate of interest on sound investments. It may be the rate at which the company can borrow money under ordinary conditions. The average rate paid on all securities is sometimes used, but in case the dividend on capital stock is fairly high, part of that should be considered as profit rather than the equivalent of an interest charge. On the other hand, if the dividend rate is fairly low and of a constant amount, it may well be considered in the category of "fair return." In some cases, due to poor financial conditions or in an emergency, a company might have to pay a higher rate for money than the market rate. All these factors should be considered in determining the rate to be used as an interest charge in figuring annual cost. It is well to keep in mind in such considerations the fact that it is *cost* which is being studied and not possible or usual return on investment. In the lack of a more carefully determined rate, 6 or 7 per cent is quite commonly used.

Taxes.—Taxes are an annually recurring expense on any piece of property. The percentage which should be included in annual costs to represent taxes may usually be quite easily determined from the company's accounting records. It should include all taxes, both direct and indirect, property tax, income tax, etc.

Right-of-way.—Any yearly payment for right-of-way for a pole line must, of course, be included in the annual costs of the line. It partakes of the character of rental of the property occupied, which rental of course represents the annual charges which would be incurred on the same property if it were owned. Right-of-way costs are the most usual form of rental encountered on a distribution system, but any other form should be similarly included. Rental of pole space on jointly occupied poles is, of course, merely another type of right-of-way charge, or rental.

Insurance.—Insurance is not a usual cost on distribution lines, but should be recognized as an annual cost where it does occur. It may include insurance against loss by fire, theft, tornado, etc.

Maintenance.—Maintenance charges include all the expenses which become necessary in keeping the property in good working condition during its useful life. Patrolling lines and transformer inspecting and testing are forms of maintenance which can be foreseen and whose cost can be quite accurately estimated. The former is proportional to the length of line but does not enter into problems such as those of wire size. The latter is proportional to the number of transformers but not to their size. Repairs which become necessary because of failures due to faulty material or unforeseen loads are impossible to anticipate with certainty, but experience will show a more or less constant average for a large group of similar units. Such a cost is likely to be practically proportional to the size or cost of the unit and the average annual cost can be distributed as a part of the annual charge on the investment. Certain other major items of maintenance are impossible to foresee and can only be included as an approximate figure, to cover things unknown which might happen. Such a case would be the breakage of a large number of poles due to an unusually heavy sleet and wind storm. Some other work, such as the rebuilding of lines when they become deteriorated to an extent to be unsafe or unsightly or when their design becomes inadequate for the conditions which have been reached, is sometimes considered as maintenance but its cost belongs, rather, under depreciation or obsolescence.

Operation.—Some units, such as substations for example, require an expense for operation which is distinct from maintenance For distribution lines, however, such operating as is done is for the most part included, or may be included, in the class of maintenance.

Depreciation.—Depreciation is one of the elements of annual cost hardest to determine or estimate with exactness. Most materials, or at least the structures which they compose, have a limited span of life at the end of which they become unfit for service. If the property is to continue in operation after that time, provision must be made for replacing the unit when it wears out. It also may be thought of in the light of repaying the money borrowed for the initial investment when the property value represented has disappeared. In either case, a certain amount must be set aside each year out of the return from the property to offset this depreciation. Physical depreciation, that is the actual physical reduction in value, may be considered

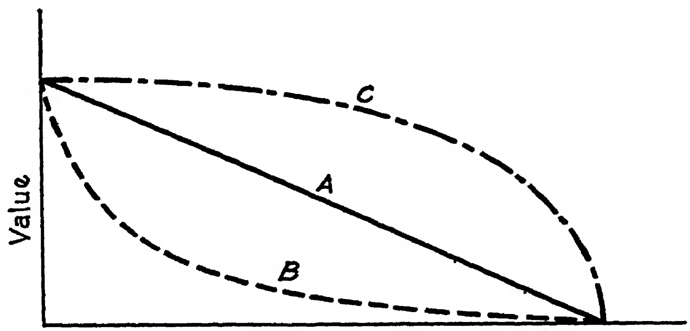


FIG. 364—Physical depreciation

as taking place in several different ways with different property. It may be gradual and uniform, about the same amount each year, such as might be the case with a wood pole which is decaying gradually until it finally becomes too weak for service. This is represented by curve *A*, Fig. 364, and is called straight-line depreciation. Other property may depreciate a large amount the first year and more gradually thereafter. This is the case with many articles whose value is measured by the amount for which they could be sold (automobiles for example), curve *B*, Fig. 364. If useful value only is considered, the depreciation may be very gradual or not at all, if the property is well maintained, until the limit of life is reached, curve *C*, Fig. 364.

When figuring depreciation as a cost charge, however, the question is not so much physical depreciation as it is the matter of taking care of replacement at the end of useful life, assuming the property as a whole will continue to operate over that life and

beyond. The straight-line assumption is often made for this purpose and is simple and easy to compute. If the allowances for depreciation are assumed to be set aside each year and allowed to accumulate *with interest,* however, the straight-line basis is incorrect, and it is logical to assume that any such fund, whether invested in the business or in other securities, would accumulate interest. This latter method of computing depreciation is called the "sinking-fund method" and naturally gives a smaller rate of annual charge than the straight-line method. For example, if a 10-year life is assumed, under the straight-line method the depreciation rate would be simply $1/10$ or 10 per cent per year. By the

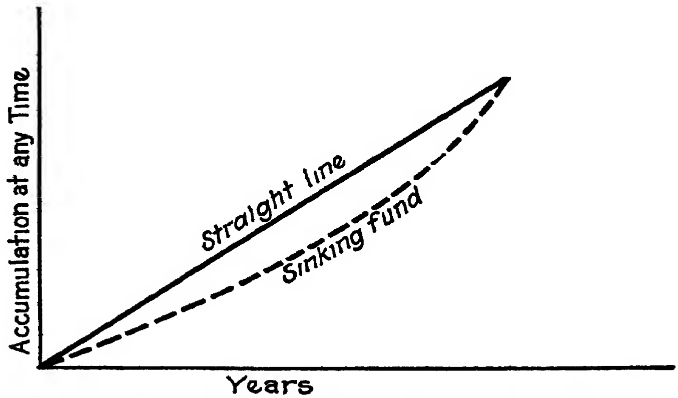


FIG. 365.—Accumulation by straight-line and sinking-fund methods.

sinking-fund method, at 6 per cent interest, the rate would be 7.59 per cent per year. In Fig. 365 the amount of accumulation at any time during the life of the material by the two methods is indicated. The formula for determining the annual rate of depreciation by the sinking-fund method is as follows:

For $1,000 at the end of n years the annual amount is equal to

$$1{,}000\,\frac{(R-1)}{(R^n-1)}, \tag{130}$$

where

$$R = 1 + \frac{r}{100},$$

r = rate of interest assumed, in percentage.

The *rate* of depreciation by this method is therefore the above divided by 1,000, times 100 or

$$100\frac{(R-1)}{(R^n-1)} \text{ per cent.} \tag{131}$$

The salvage value of material must be taken into account when computing depreciation. A pole for example may be rotted at the ground line so as to be unserviceable and yet it may be possible to remove it, saw off the butt, and use it again as a shorter pole. Copper wire may become unserviceable on account of the deterioration of insulation or weatherproof covering, or due to breakages, but the copper itself has little physical depreciation and may be sold for a relatively high price. The depreciation must therefore be figured on the *reduction in value*, allowing for the salvage value recovered. A simple example of a computation for depreciation will illustrate this:

Assume a line of No. 0 weatherproof covered wire.

Cost of wire per 1,000 ft.—420 lb. at $0 17	$71 40
Labor cost of erection	10 00
Total	$81 40
Salvage value, 319 lb. at $0 12	$38 28
Labor cost of salvaging	10 00
Net salvage value	$28.28
Net Cost	$53.12

Assuming a life of 15 years, on the

$$\text{straight-line basis, depreciation} = \frac{\$53.12}{15} = \$3\ 54$$

$$\text{or} \quad \frac{\$3.54}{81\ 40} = 4 \text{ per cent per year}$$

$$\text{on the sinking-fund basis, depreciation} = \frac{\$2\ 28}{81\ 40} = 2.8 \text{ per cent per year.}$$

As indicated in the above example, labor costs for dismantling and removing the material enter into the net cost on which depreciation must be computed.

Obsolescence.—Materials and structures often are replaced long before their useful life has expired, on account of the fact that they have become undesirable due to changes in the art, changes in conditions under which they are used, changes in regulations governing their use, introduction of more efficient and economical designs, replacement of other materials with which they are used, etc. It is practically impossible to foresee most of such changes and yet it must be recognized that they are likely to occur. One very simple method of allowing for this factor is by using the straight-line method for figuring depreciation, understanding that it is not correct as far as actual depreciation is concerned,

but allowing the excess rate (over the sinking-fund rate) to be a provision for obsolescence.

Total Annual Charge.—It is usually convenient to assemble all the above component charges into a total annual charge percentage which may be applied to the initial cost of the structure in place, to determine the annual cost.

For example,

	Percentage
Interest	6.0
Taxes	2.5
Maintenance	0.5
Depreciation	6.0
Total	15.0

CHAPTER XXXIII

COST OF ENERGY LOSSES

The determination of the cost of energy with any degree of exactitude is usually a rather difficult matter So many variable and uncertain quantities are involved, whose interrelationships are also rather indeterminate, that it may sometimes be almost a hopeless task to arrive at any accurate solution. However, it is essential for the purpose of making economic studies, that the cost of energy losses be as near to actual costs as they can be determined. Otherwise, the results obtained will not be indicative of true conditions. Doubtless, in most cases, a number of assumptions and approximations will have to be made in the course of a study of energy costs, but in any case an approximation based on careful study of the governing factors will be far better than a mere guess. It is intended to show here what are the governing factors and what their effect is on energy cost rather than to indicate a definite method of computing such cost. The method of computation used will depend somewhat on the type of system and the purpose for which the cost data is to be used.

The cost of energy delivered at any one given point on the system may be considered as somewhat different from the cost at any other given point. Similarly, the cost of each kilowatt-hour at any given point may be somewhat different from the cost of any other kilowatt-hour at that point. This will be recognized when it is remembered that the cost of energy depends somewhat on the shape and size of the characteristic curve of the load being considered and its relation to curves for other types of loads and to system load, and that it includes the cost of distribution up to the point of utilization. Furthermore, since losses vary as the square of the load, the line losses per kilowatt are greater for a large load than for a small one, and cost of losses in distribution are a part of energy cost. It is of course impossible and unnecessary to go to any such degree of refinement in considering energy costs. Loads fluctuate from day to day and year to year, both as

to size and as to shape of load curve, and methods of system operation change from time to time. It is sufficient to deal with large groups or classes of load and to obtain average costs for such groups.

It is well to keep in mind, in studying energy costs for use in economical design, that there is a fundamental difference between such costs and the costs which are determined for rate-making purposes. For use in setting up a rate scale, it may be sufficient to consider the system as a whole and obtain the average cost per unit for each of a few general classes of loads which have markedly different characteristics. The rates may be the same all over the system and it is the grand average cost which is important rather than the specific cost for any particular locality. The chief object is to so determine the cost that it may be covered by the return received from the customer. In economical design, on the other hand, the true cost to the company is the important feature. In many cases, energy losses may be reduced by an increase in investment and the problem is to justify or condemn such increase. To accurately represent the economics of the situation, therefore, the value used in computing the savings due to decreased losses must represent true costs of energy losses at that particular point and not the average for a whole system. The cost at outlying points for example will be greater than near the generating station and hence the savings accomplished by their reduction are more important. It is evident, therefore, that, whereas it is necessary from a practical standpoint to make certain assumptions and to use average values in determining the cost of energy, it is also of advantage to investigate the variation in cost in as much detail as is warranted by the accuracy and detail of the information available.

Another point which it is well to observe is the distinction between actual cost and the *apportionment* or assignment *of that cost* among different loads when determining the rates to be charged. The important consideration for this work is how actual cost will be increased or decreased by any proposed change in the system and not how that increase or decrease may be distributed among the customers. This point will be discussed further under demand costs.

Classification of Costs.—The costs incurred in producing electrical energy and delivering it at the point of consumption include the following items:

a. Annual charges (see Chap. XXXIII) on investment in generating station land, buildings, generating equipment, etc

b Cost of operating generating stations including labor, fuel, lubricants, station supplies, etc.

c Annual charges on investment in transmission lines, substations, and distribution lines from the generator to the point of utilization.

d Cost of energy losses experienced in transmitting the energy to the customer.

e Cost of operation of substations and lines

In addition to the above, further costs are involved which influence the net return received, *i e*,

f. Cost of metering, billing, collecting, service costs, lamp renewals, etc.

The various costs indicated may be subdivided and classified as follows:

1. Costs dependent on the *number of customers*.
2. Costs dependent on the *peak load* carried on the system or the *demand*.
3. Costs dependent on the total *output in kilowatt-hours*.

This classification was proposed by Dr. John Hopkinson in England in 1892 and has been later discussed and amplified by H. L. Doherty and other writers. It is quite generally accepted for ordinary purposes. There are other minor classifications of course, into which certain costs might be placed but these three are the most important and practically all costs can be divided among them without introducing appreciable error.

Customer's Cost.—The first class of costs mentioned, *i.e.*, customer's cost usually may be omitted in considering energy cost for economic study, as such costs are not really energy costs but costs incurred in collecting the return received for the energy. Care must be taken, however, that costs belonging in that class are not included under either of the other divisions. Here, rightfully, belong the greater part of general office expense, sales expense, costs of metering, billing, and collection, part of the cost of service wires, and some percentage of other costs according to local conditions.

Demand Cost.—The second division of costs, demand costs, includes all the costs on generating station, transmission lines, substation or distribution lines, which are dependent on the total amount of load carried—the peak load. If that peak load is 100,000 kw., the generating station must have a capacity of 100,000 kw. plus a reasonable amount of reserve for emergency, even though the load of 100,000 kw. is reached for only a short

time at some time during the year. Similarly, the transmission lines, substations, and distribution lines must be large enough to handle the maximum load which they are called upon to carry at any time, even though the load for the greater part of the time may be very considerably less. The investment necessary, therefore, is governed by the demand (kilowatts) and not by the amount of use (kilowatt-hours).

Some items of annual cost clearly belong to demand cost only. These are such costs as interest, taxes, insurance, etc., on the generating station building, land, boilers, turbines, and other equipment, and similar charges on investment in transmission lines, substations, and distribution lines. These costs have, as a rule, no relation to the number of kilowatt-hours produced and are strictly demand charges. Other costs may be attributed partly to demand and partly to output. For example, the cost of fuel, while very largely proportional to the kilowatt-hours produced, is still in some part a demand charge, since it will take some fuel to keep steam in the boilers ready for operation, even though no kilowatt-hours are produced. Similarly, wages of station attendants, cost of lubricants, depreciation on certain machinery, etc. are items which are affected to a greater or less degree by the demand.

Output Cost.—The remaining parts of the items just mentioned, *i.e.*, the parts not attributable to demand, may generally be considered as proportional to output or kilowatt-hours. The cost of energy losses experienced in transmitting and distributing the energy is also very largely an output charge. The cost of core losses in transformers may be considered as a demand charge since they are continuous regardless of the amount of load carried. The cost of copper losses (I^2R losses) is strictly an output cost but is not directly proportional to the output in kilowatt-hours. The total amount of loss depends on the shape of the load curve since the loss at any time is proportional to the *square* of the load, see Fig. 367. Two loads might consume the same number of kilowatt-hours and yet might cause quite different amounts of loss. This may be clearly seen by referring to the discussion of load factor and loss factor in Chaps. III and XI.

The proper proportion of any cost to assign to demand and to output may be somewhat difficult to estimate and will no doubt vary with different systems. One method of making a determination of this division, based on actual total operating costs,

is as follows: Two periods are chosen, such as a month or a week at different times of the year, one in which the load is heavy, the other in which the load is light. If

C_D = demand cost per unit demand,
C_f = output cost per unit of output,
D = total demand (kilowatts),
F_1 = output (kilowatt-hours) during lightly loaded period,
F_2 = output (kilowatt-hours) during heavily loaded period,
C_1 = total cost for lightly loaded period,
C_2 = total cost for heavily loaded period,

then

$$C_1 = C_D D + C_f F_1,$$
$$C_2 = C_D D + C_f F_2,$$
$$C_f = \frac{C_2 - C_1}{F_2 - F_1}, \tag{132}$$
$$C_D = \frac{C_1 - C_f F_1}{D}. \tag{133}$$

This method can be quite easily applied to such an item as fuel cost to determine what part of it is attributable to demand.

The following is typical of the division which might be found practicable for some of the items of cost in a generating station:

	Demand, per cent	Output, per cent
Superintendence...... . .	100	
Wages.	90	10
Fuel	25	75
Lubricants	25	75
Station supplies	100	

Cost of Energy Losses.—Heretofore, the discussion has dealt with the cost of energy in general including that used as well as that lost in distribution. For the purpose of economical design, it is usually the cost of *energy losses* which is desired rather than the cost of energy delivered to the customer. The two are not greatly different. Energy loss on any portion of the system, such as a primary feeder for example, appears as a load on all of the system up to that point, and a load of similar characteristics to those of the useful load which it accompanies (with the excep-

tion that since copper losses vary as the square of the load at any time, they do not add in direct proportion to the whole load curve of the load which occasions them). The losses are hence subject to demand charges and energy charges as for any other load. One distinction might be pointed out which should be recognized although it may not always be practicable to evaluate it. Since losses are a part of the load which it is possible to reduce if desired, they must be considered as a load added to the useful load. Hence the output or kilowatt-hour cost occasioned by *copper losses* on the system up to the point where the losses under consideration occur, is somewhat greater for such losses than it is for the useful load. This may be illustrated by a simple example. If the useful load on a power line is assumed to be 100 per cent, and the losses on that line 10 per cent, the total load transmitted to that point is 110 per cent. The copper losses on the system up to that point are proportional to the load squared, hence, for the useful load, they are proportional to 100 per cent and for the total load (110 per cent) they are proportional to 121 per cent. Therefore, the transmission losses for the 10 per cent loss in the power line are proportional to 21 per cent or are over twice as much per unit as for the useful load.

For practical use in economic problems, several different assumptions are sometimes made as to the proper value to place on energy losses. These will be discussed briefly.

1. It is sometimes assumed that the energy lost should be charged at the price received for useful energy at the point of delivery, *i.e.*, the price for which it might be sold if it were delivered instead of dissipated in heat along the lines. This theory takes little account of the actual cost of the energy as discussed above. If the energy supply is *limited* and the demand for it is greater than the supply, this assumption would seem reasonable since any additional energy which can be delivered by reducing losses could be sold for the regular price and cannot be obtained otherwise. Such a case is rather unusual, however, appearing perhaps only in such cases as small, isolated hydroelectric plants, etc. Under the more usual conditions, the supply could be augmented, by additional investment, to care for any losses occasioned in serving all the available load.

2. Another assumption which is sometimes made, is that the demand cost for losses should be distributed among losses occasioned by various types of load (power, lighting, street railway,

etc) in the same proportion by which demand costs for energy used is allocated to these same types of load in determining rates to be charged. The method of allocating demand costs will be taken up briefly later. This theory usually confuses actual cost with the method of distributing that cost among the various customers in collecting a return to cover that cost. The latter is a commercial problem such as any merchant has in determining the prices which he can reasonably charge in order to regain the investment which he has made in a quantity of goods (plus reasonable profit) but does not affect to any extent the price he has paid for the goods. This theory of distribution of demand cost can therefore only be considered justified when the problem involves the collection of a return from the customer for the energy losses, and not when only cost to the power company is considered.

3. The theory which more nearly represents the true cost in most cases is that the demand cost is proportional to the part which the particular load (or loss) in question plays in the peak demand. It has been indicated that demand cost on a generating station, or on any other part of a system, was dependent on the peak load or demand on that station or part of the system. If, therefore, a particular type of load, such as lighting load causes only some fraction, such as one-third of the peak demand, it is responsible for only one-third of the demand cost.

A simple example will illustrate the theory and also bring out the relations in regard to demand cost *per unit of demand* (per kilowatt). Assume two loads as indicated in Fig. 366, one having its peak at time of system peak, the other having its peak at some other time and entering the system peak in only a fraction of its own peak. Load *A* has a peak of 75,000 kw. at 9 a.m. at which time the system peak of 100,000 kw. occurs. Load *B* has a peak of 50,000 kw. at 8 p.m. but at 9 a.m. it amounts to only 25,000 kw. or one-half of its own peak and one-fourth of the system peak. Assume, for simplicity, that the total annual demand cost has been determined as $1,600,000 or $16 per kilowatt of peak load. Load *A*, therefore, is responsible for $1,200,000 of this and load *B* for $400,000.

If, now, the load curves are assumed to be definitely characteristic, *i.e.*, each component part of load *B*, for example will have half as much load at 9 a.m as it does at 8 p.m., etc., the demand cost may be expressed in cost per kilowatt for each type of load,

the kilowatts referred to being kilowatts at time of its own peak for each load (at 8 p.m. for type *B*). For load *A* then, the annual demand cost per kilowatt is $1,200,000/75,000 = $16 per kilowatt since its peak occurs at time of system peak. For load *B*, however, the demand cost per kilowatt will be $400,000/50,000 = $8 per kilowatt since its peak occurs at some other time than time of system peak and its load at time of system peak is only one-half as much as its own peak.

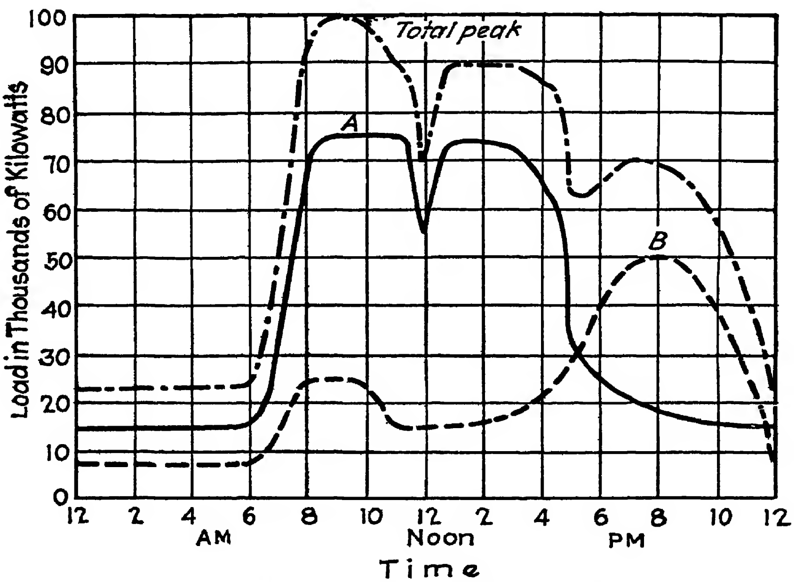


FIG. 366.—Combination of two loads

It may be stated therefore that the *demand cost per kilowatt for any load whose peak occurs at time of system peak is equal to the demand cost per kilowatt of system peak load, while the demand cost per kilowatt of a load whose peak occurs at some other time than time of system peak is equal to the ratio of its load at time of system peak to its own peak, times the demand cost per kilowatt of system peak.*

A further consideration enters the problem of demand cost for energy losses. Figure 367 shows the relation of copper losses to load, at any point on the load curve, the loss being proportional to the square of the load. It is evident, therefore, that, if the load at time of system peak is only one-half of its own peak, the copper loss at that time is only one-fourth the loss at peak load.

Therefore the *demand cost for copper losses for an "off peak" load is equal to the square of the ratio of its load at time of system peak to its own peak, times the demand cost per kilowatt of system peak.*

In the problem shown in Fig. 366, the demand cost for losses for load B would be only \$16/4 = \$4 per kilowatt. This is evident when it is considered that if the losses for load B were, for example, 8,000 kw. at time of its peak, at time of system peak, when the

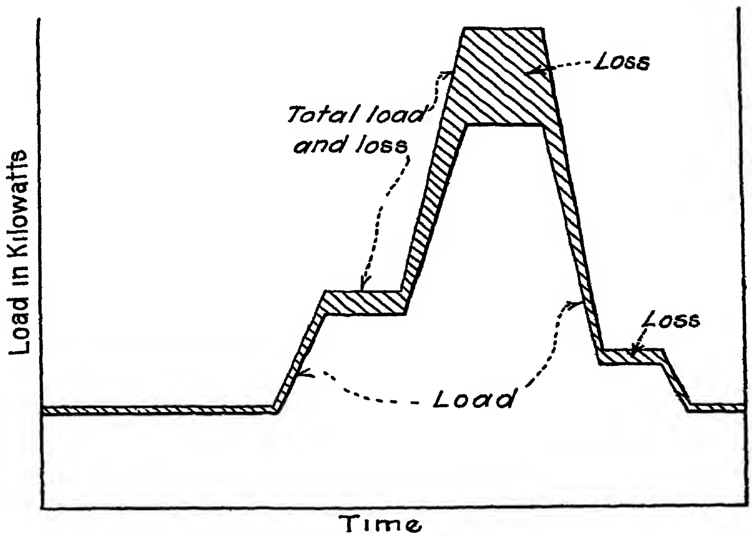


FIG. 367.—Relation of copper loss to load.

load is only one-half as great, the losses would be only 2,000 kw. The corresponding demand cost would therefore be \$32,000/8,000 = \$4 per kilowatt of loss.

This theory can be applied to the determination of demand costs on any portion of the system, transmission, substation, etc., the corresponding load curves being used for each part. It should be remembered that a given load may play a different part in the peak load on various parts of the system. Lighting load for example may be "off peak" for the generating station and transmission lines and yet create the peak on its own part of the distribution system, taking full demand cost for that part. It is also well to remember, in computing demand costs, that loads which are off peak now may change so as to create the peak at some other time.

Allocation of Demand Costs to Loads.—It has been mentioned (under Cost of Energy Losses, 2) that the methods of allocating demand costs among various types of loads for rate making were sometimes used for distributing costs of energy losses. It will be of interest to mention briefly some of the methods used for that purpose.

1. The allocation of costs according to the share the load has in the system peak (as discussed under Cost of Energy Losses, 3) may be used sometimes, but not often, since it is likely to favor the off-peak customer too greatly.

2. The costs are sometimes allocated in proportion to the peak values of the various component loads.

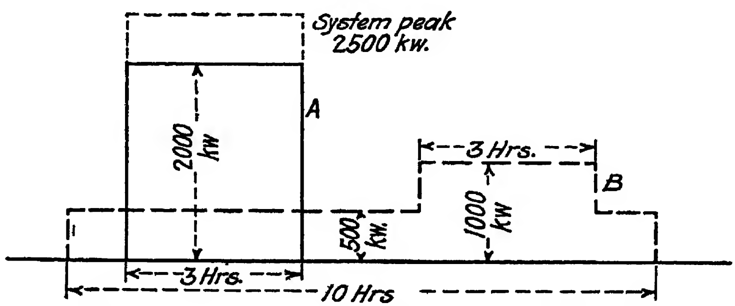


FIG. 368.—Example of allocation of demand costs

3. The use factor is sometimes considered and this probably gives the fairest distribution. By this is meant that consideration is given to the amount of time which the customer makes use of certain parts of the system capacity, as well as simply his part in the peak.

Referring to Fig. 368, let A and B be two different loads, carried on the same system. A has a steady load of 2,000 kw. for 3 hr., B, 500 kw. for 10 hr. with an additional 500 for 3 of these hours but not the hours which A is using. The total demand cost is based on the peak load of 2,500 kw., 2,000 of which is A's and 500 B's.

The division of demand cost would be under method 1,

$$A \ldots \frac{2{,}000}{2{,}500} = \frac{4}{5} \text{ of total demand cost,}$$

$$B \ldots \frac{500}{2{,}500} = \frac{1}{5} \text{ of total demand cost.}$$

under method 2,

$$A \ . \ . \ . \ \frac{2{,}000}{3{,}000} = \frac{2}{3} \text{ of total demand cost,}$$

$$B \ . \ . \ . \ \frac{1{,}000}{3{,}000} = \frac{1}{3} \text{ of total demand cost.}$$

Under method 3[1], the total system might be divided into part systems of 500 kw., 500 kw. and 1,500 kw. *B* uses 500 kw. entirely for its own load. It uses the other 500 kw. for 3 hr., while *A* uses it for another 3 hr., *A* uses the 1,500 kw. entirely. Therefore,

$$A \ . \ . \ . \ \frac{1 \times 1{,}500 + \frac{3}{6} \times 500}{2{,}500} = \frac{1{,}750}{2{,}500} = 0.7 \text{ of total}$$

$$B \ . \ . \ . \ \frac{1 \times 500 + \frac{3}{6} \times 500}{2{,}500} = \frac{750}{2{,}500} = 0.3 \text{ of total}$$

Many variations of these methods are possible, but the above is sufficient to indicate the general problem.

Summary of Cost Analysis.—It is desirable to obtain as complete a schedule as possible of demand and output costs for various parts of the system. Various problems arising involve the cost of energy losses at different points, such as on transmission lines, at substation transformers, on primary feeders, at distribution transformers, etc. The more accurately the costs at these various points can be differentiated the more accurate the solutions obtained for such problems.

Figure 369 indicates the factors which must in general be taken into account in carrying out a complete analysis of energy costs on a system.

Application of Energy Costs.—There are, of course, many occasions when such a complete detailed analysis is impracticable on account of lack of time or lack of complete data. Approximations are entirely justified if they are made intelligently with a knowledge of what the true affecting conditions are. A common approximation is to assume the demand costs on a generating station to be simply the annual charges on the total investment represented in station and equipment, and the output cost, the total operating expense of the station, including all fuel, wages, etc. On transmission lines, the demand cost is represented by annual charges on investment and output cost is the cost of losses

[1] Eisenmeyer, H. E., "Central Station Rates in Theory and Practice."

on the line. Such a method will no doubt give results not far wrong in the final solution if all costs are included in one or the other division. The figures used may be qualified somewhat,

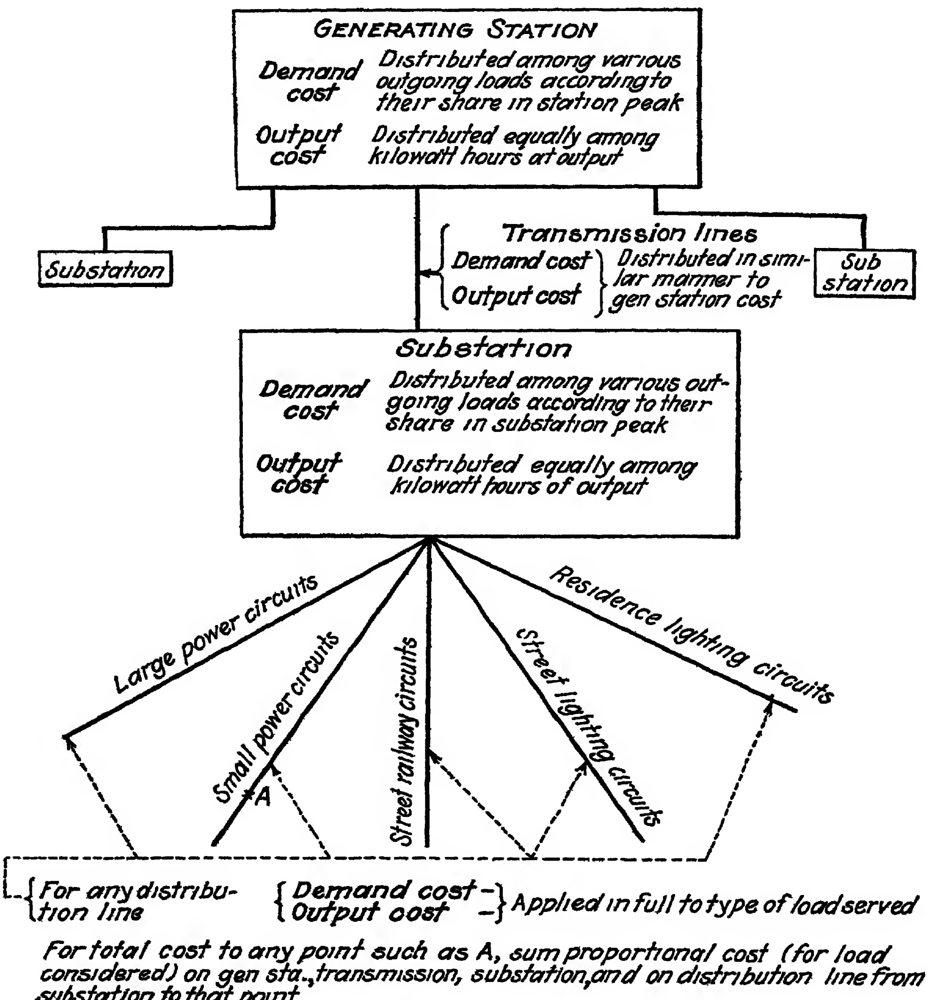


FIG. 369.—Factors entering in to energy cost.

if desired, to allow for the other variations indicated in the preceding discussion.

When using costs of energy losses in actual problems there are two methods, in general, in which they may be handled:

1. Demand costs and output costs may be kept separate. The demand cost per kilowatt is multiplied by the demand occasioned by losses. The output cost per kilowatt-hour is multiplied by the kilowatt-hours of losses per year.

2. The demand cost may be reduced to a cost per kilowatt-hour for the particular type of load and added to the output cost, giving a single cost per kilowatt-hour. This form is perhaps somewhat more convenient to use in most problems.

In any computation of annual costs due to energy losses, whether by the former or the latter method, it is necessary to obtain the total number of kilowatt-hours for the year corresponding to the loss in kilowatts at peak load, since the latter figure is the one usually determined first. Reference should be made to the discussion of *loss factor* and *equivalent hours* in Chap. III. Total kilowatt-hours for a year are given by

$$\text{Kilowatt-hours of loss} = \text{kilowatts of loss} \times t \times 365,$$

where

t = equivalent hours per day which peak load must continue to give a total loss equal to that actually experienced,
= loss factor $\times$ 24.

If

C_1 = demand cost per kilowatt for losses,
C_2 = output cost per kilowatt-hour for losses,
C_3 = combined cost per kilowatt-hour as indicated in method 2.

(1) Annual cost of energy losses =

$$\text{kilowatts of loss} \times C_1 + \text{kilowatts of loss} \times t \times 365 \times C_2. \quad (134)$$

(2) Annual cost of energy losses =

$$\text{kilowatts of loss} \times t \times 365 \times C_3. \quad (135)$$

$$\text{Evidently therefore } C_3 = \frac{C_1}{t \times 365 + C_2}.$$

Example of Computation of Energy Cost.—An example of a computation of cost of energy losses will now be given to indicate concretely some of the principles given above. A simple power system will be assumed as indicated in Fig. 370. The quantity desired is the unit cost of energy losses occurring on lighting secondaries. It is assumed that the lighting load is fed by separate circuits from the substation. The substation, however, carries diversified load as indicated by the separate power

circuits shown, hence the peak load on the substation does not occur at the time of the lighting-load peak. At the time of the substation peak the lighting load is only one-half of its peak value (see Fig. 366). The same is therefore true in regard to the load on the transmission line and the generating station. The values assumed for investment costs, percentage of losses, etc., are shown in Table LI.

The difference in the figures in columns 2 and 3 is due to the difference between system capacity and actual peak load.

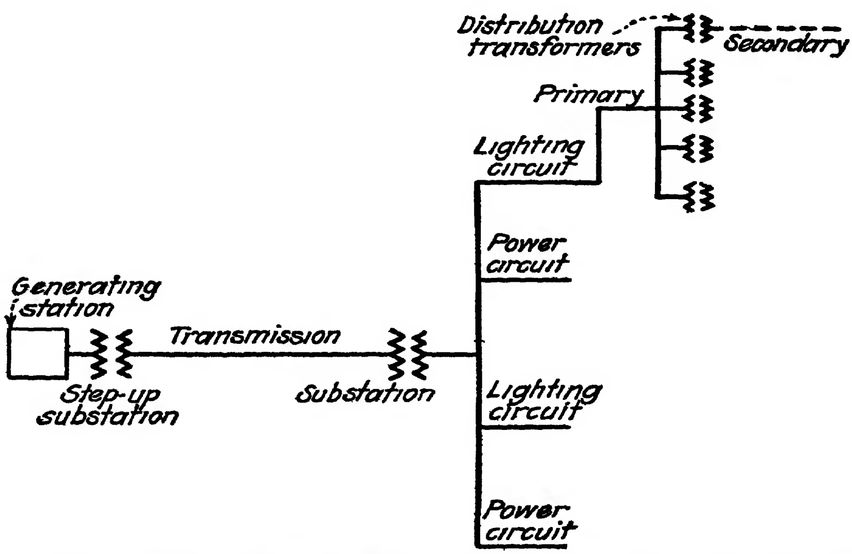


FIG. 370.—Diagram of system used in computing example of energy cost.

The percentages in column 5 were derived from those in column 4, using comparative values of load factor and loss factor.

The figures in column 7 were obtained by progressive application of the per cent losses in column 4. The multipliers in column 8 take account of the percentage of load at the time of peak load, squared to get values for *losses* rather than *loads*.

Costs in column 9 were obtained from columns 3 and 8.

Kilowatt-hours in column 10 were obtained by progressive application of the percentages in column 8 and represent the addition to output cost occasioned by line losses.

The yearly cost of core loss was added to demand charge, the figure 0.026 representing the total per cent core loss

from column 4, increased to allow for additional output cost on the system for these losses.

This computation introduces some approximations, such as the neglecting of diversity factor, but it illustrates many of the chief points to be observed in making such a determination. A number of refinements are possible if it is desired. It should not be assumed that the figures given apply to any particular system. They were selected at random.

TABLE LI.—COMPUTATION OF ENERGY COST

1	2	3	4	5	6	7	8	9	10
	Investment per kilowatt capacity	Investment per kilowatt peak load	Per cent loss, peak (kilowatts)	Per cent loss, output (kilowatt-hours)	Percentage of lighting peak at time of peak load	Kilowatts at peak for 1 kilowatt on secondaries	Multiplier for demand charge for loss	Demand charge per kilowatt for losses	Kilowatt-hours for kilowatt-hours on secondary
Secondary	$ 20	$ 25	2	0 8	100	1	1	. ...	1
Distribution transformer	20	25	2 copper 0.6 core	0 8	100	1 026	1.026 × 1	$ 25 70	1 008
Primary	12	15	5	2	100	1 078	1 078 × 1	16 20	1 028
Substation	30	40	1.5 copper 1 core	1	50	1 105	1 105 × $0\ 5^2$	11 15	1 038
Transmission	12	15	5	3	50	1 16	1 16 × $0\ 5^2$	4 36	1 069
Step-up substation	12	15	1 copper 0 8 core	0 7	50	1 187	1.187 × $0\ 5^2$	4 46	1 080
Generating station	100	130	.	.	50	1.187	1 187 × 0.5^2	38 70	1 080
Total		.		.	. .	.	. .	$100 57	

Annual charges at 15 per cent $15 10
Annual core-loss cost 0.026 × 24 × 365 × 0 005 . . $ 1 14
Total demand charge . . . . $16.24 per year

Output charge at generating station 0 005 per kilowatt-hour,

0 005 × 1 08 = 0 0054 at secondaries.

C_1 = demand charge per kilowatt = $16 24.
C_2 = output charge per kilowatt-hour = 0 0054

$$C_3 = \text{combined charge per kilowatt-hour} = \frac{C_1}{365\,t} + C_2 = \frac{16\ 24}{912.5} + 0\ 0054$$

$$= 0\ 0178 + 0\ 0054 = 0\ 0232$$

(assuming t = 2 5 hr. per day).

CHAPTER XXXIV

GENERAL METHODS

Before proceeding to a discussion of specific problems relating to particular parts of the distribution system, an analysis will be given of the general methods of attacking such problems. While each problem of this kind may present certain characteristics of its own which make it different from all others, there are certain fundamental principles and methods which will be found useful in indicating the process to follow in seeking a solution. A thorough understanding of these fundamentals will greatly simplify the work of economic study in any case.

Preliminary Work.—It is assumed at this point that cost studies of materials, construction, annual charges, and energy costs have been made, as suggested in the previous chapters, and definite values assigned to the various items. These are the tools to be used in the more specific work of determining the most economical conditions of design and operation of the system.

It may be almost needless to say that a prime requisite for attacking any problem is a definite statement of just what the problem includes and the object sought. It may be the most economical span for a line, the most economical wire size, the most economical voltage, the most economical voltage drop, a choice between two specific alternatives (such as two different routes), or other similar questions. In any case, the objective should be clearly defined.

The second requisite is a determination of all the limiting factors in the case. For example, in studying the most economical span for a line, the size of conductor will be a governing consideration. The conductor must be large enough to carry the electrical load with satisfactory voltage regulation. Then, there may be several materials which would make suitable conductors. These must be chosen and their characteristics studied. Finally, there may be certain local limitations imposed on span lengths, wire sizes, sags, strengths, safety factors, spacings,

etc., by safety codes or rules which govern in that locality. All these factors enter into the problem and limit the field of study. As another example, in determining the most economical wire size for a given load, there will be a minimum limit of size which will be practicable for mechanical strength, a minimum which will be satisfactory from the standpoint of carrying the electrical load, and possibly a maximum size which can be used without increasing the strength of the supporting structures. It is to be recommended that all such limitations or restrictions in connection with any problem be investigated before the actual consideration of costs is begun. In general, it might be said that at least a certain amount of study of the electrical and mechanical design should usually precede the economical design, as these fix the limitations. In any problem dealing with wire sizes, voltages, etc., it is also necessary to definitely define the electrical load to be used. It may be that the load is increasing from year to year. If so, the rate of increase should be estimated. The economical condition may be determined for present load, for the load some definite time in the future (based on the assumed rate of increase), or the rate of increase of the load may be included as a factor in the problem.

One other general consideration should be mentioned. The problem may be a simple one, involving only one variable whose economical size is to be determined, such as the economical size of a conductor, when pole strength is not a limiting factor. It often happens, however, that there is more than one variable. Such is the case in studying the design of secondaries. The wire size, transformer size, transformer spacing, and voltage drop, are all variables subject to economical determination. They also have interrelated effects, each on the others, and it may not be possible to determine any one separately. Some preliminary study of any problem, with this question in mind, is worth while, to determine what factors are variable, which ones are independent, and what interrelations must be studied to reach a correct solution.

General Cost Equation.—After the preliminary consideration of the problem has been completed, all the elements of cost entering the problem should be set down. Some of them may not be variable but it is well to include them all to be certain that none have been omitted that do have an effect, even indirectly. It is convenient for this purpose to use an equation of total cost.

Such an equation is illustrated. It will be somewhat different for different problems, but the items included are characteristic of those commonly encountered.

Let g = percentage total annual charges attributed to any class of property (g_1, g_2, g_3, etc., indicate values for the different classes represented).

Then,

total annual cost = g_1(cost of right-of-way)
+ g_2(cost of poles and fixtures in place)
+ g_3(cost of conductors in place)
+ g_4(cost of any special equipment in place)
+ cost of maintenance, inspection, testing, etc.
+ cost of annual energy loss in conductors
+ cost of annual copper loss in transformers
+ cost of annual core loss in transformers, etc.

Such an equation as the above might be written for a problem involving the determination of a most economical primary voltage. For some problems the equation would be more simple. What it is wished to emphasize, however, is the value of definitely setting down in such an equation, the cost factors which affect the problem. It clarifies the solution as it lists specifically the various costs which must be determined.

In handling the cost equation for making graphical comparisons and mathematical solutions for *most economical conditions*, it is convenient to represent all the elements possible by symbols. The solution is thus facilitated as some of the quantities drop out and the resulting expressions are of more general application to other problems than the one in hand. For example, such factors as cost of energy, load density, wire size, voltage drop, cost of copper, maximum load, transformer size, etc., may all enter the equation in the form of symbols to be evaluated after the solution is completed.

Methods of Comparing Costs.—There are various methods of comparing costs, which may be fitted to the problem in hand as best suits the conditions. Some of these are as follows:

1. Direct comparison of the total amount of cost or of annual cost. This is the simplest method, of course, but is suitable for only the simplest problems, such as the comparison of two spe-

cific designs whose costs can be definitely figured. For more general problems the use of graphs or charts is usually advisable.

2. Plotting the equation for total annual cost in terms of the variable being studied. Such a chart is shown in Fig. 371 assuming that the variable is wire size, *i.e.*, it is desired to compare annual costs for various wire sizes. The advantage of this

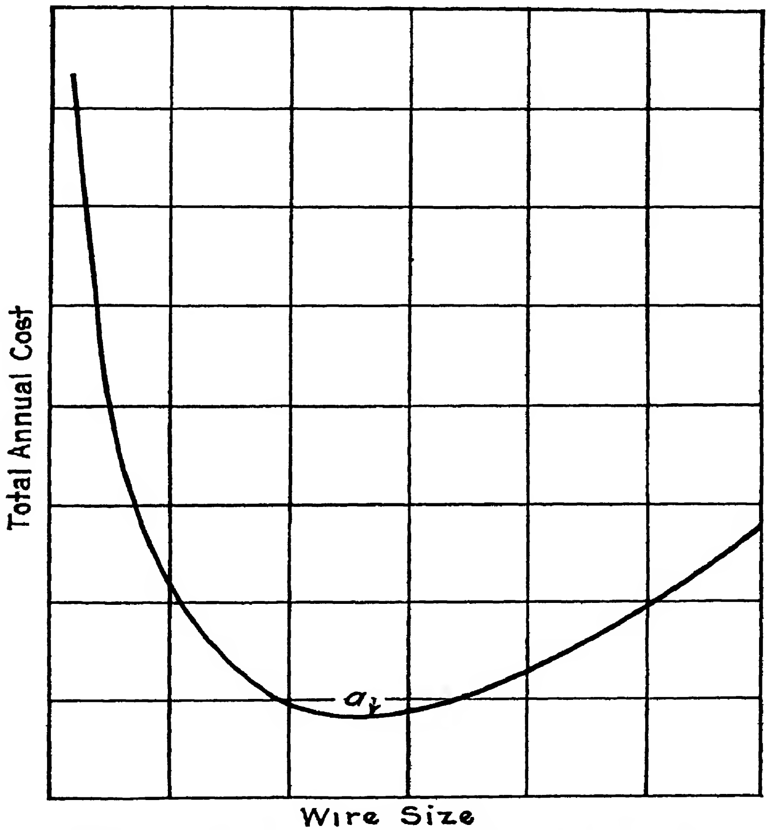


Fig. 371.—Total annual cost plotted—two variables

method is that not only is the most economical size indicated at *a*, where the cost is least, but also the difference in cost between different sizes is evident. It is often desirable to know how much extra a particular size will cost than the most economical, in order to compare that extra cost with other less tangible advantages.

If there is more than one variable (besides annual cost) the total cost may still be shown graphically by taking one variable

in steps and plotting a curve of cost for each step. Figure 372 shows such a chart where the two variables are wire size and loading, the annual costs being given in cost *per kilowatt* of load rather than total cost, in this case, to reduce all curves to the same

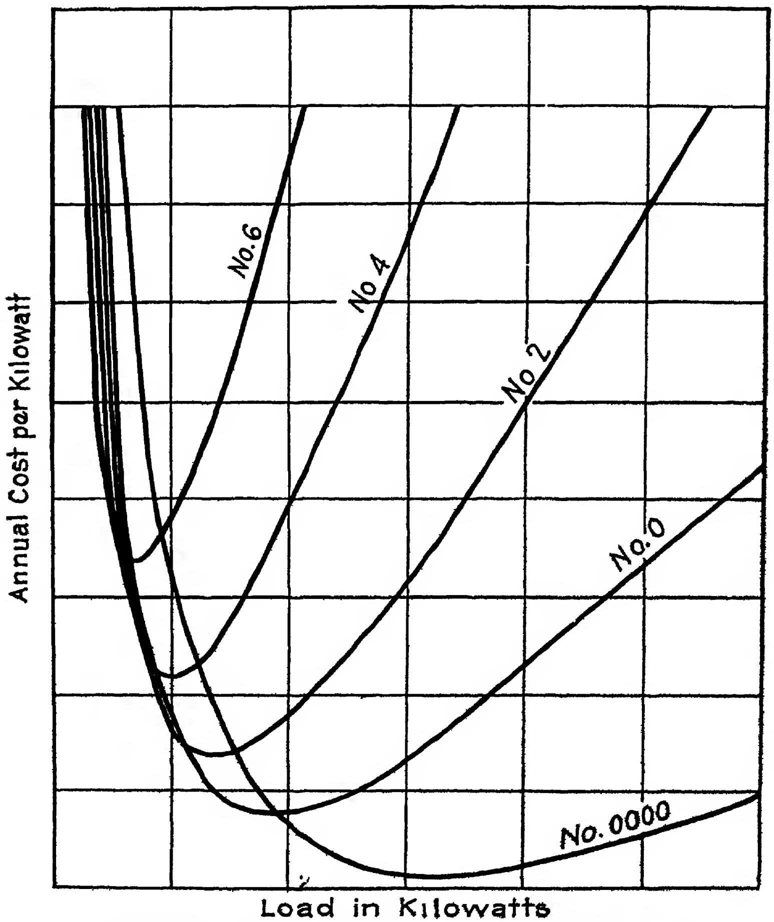


FIG. 372.—Annual cost plotted—three variables.

basis. From such a curve the most economical size of wire for any load can be determined, also the difference in cost between that size and any other size, and also the change in cost per kilowatt as the load increases, indicating perhaps at what point one wire size should be replaced to a larger size and the size to be used.

3. A convenient method where there are three variables besides annual cost in the equation is to take one variable in steps as was

done in (2), writing a cost equation for each step. Another variable is then eliminated by solving simultaneously the equations of adjacent steps, the graphs of the resulting equations showing the points where the economy changes from one step to the next. This can best be illustrated by an example. Assume a problem of determining the proper wire sizes for three-phase secondaries, the load in horsepower being one variable, the number of hours per week the load operates another variable, and wire size, of course, the third. Cost equations are first written for each standard size of wire used on the system, Nos. 6, 4, 2, etc., up to No. 0000. (These are the "step" equations.) The general cost equation would be of the form

$$Y = K_1 + K_2A + \frac{K_3}{A}t\overline{HP}^2, \tag{136}$$

where

Y = total annual cost
A = cross-sectional area of conductor.
t = hours per week.
HP = horsepower of motor.
K_1, K_2, K_3 = constants for the problem.

Eliminating A by writing an equation for each wire size, these equations would be of the form

$$Y_A = K_4 + K_5t\overline{HP}^2. \tag{137}$$

If equations for A_1 and A_2 (two wire sizes) are solved simultaneously by assuming Y_A the same in both cases, the result is a series of equations of the form

$$t\overline{HP}^2 = K_6, \tag{138}$$

where the costs for size A_1 is equal to that for A_2. These may be plotted as shown on Fig. 373 using t and HP as the coordinates. The resulting graph must be considered as a series of *areas* divided by the curves. For any point lying in the area designated as No. 2, the No. 2 size of conductor is more economical than either adjacent size. For a point *on* any line, there is no choice between the two sizes which the line divided.

Such a chart is more or less special in character but is sometimes quite useful as a reference to a field engineer when numerous small problems of similar character must be solved quickly. It has the disadvantage of not showing comparative costs quantitatively but this is hard to do with so many variables. The

Contrary to a very prevalent impression and belief, the gauge to be chosen for the conductor does not depend on the length of it through which the energy is to be transmitted. It depends solely on the strength of the current to be used supposing the cost of the metal and of a unit of energy to be determined."

In expressing this theorem mathematically, the total annual cost was given as the sum of annual charges on the investment cost of the conductor, and the annual cost of energy losses. This equation is of the form given above, K_1 being costs not depending on wire size, K_2 being charges proportional to wire size (investment costs), and K_3 being charges inversely proportional to wire size (energy costs). The minimum cost shown by the solution of such an equation is when the two costs are equal, *i.e.*, when $K_2A = K_3/A$. This is evident from the expression above for dY/dA. If

$$K_2 - \frac{K_3}{A^2} = 0,$$

$$K_2A = \frac{K_3}{A}.$$

What is generally known as Kelvin's law has been formulated from this relation. It is generally expressed as:

The most economical size of conductor is that for which the annual charge on the investment is equal to the annual cost of energy loss.

This law is a very useful rule for rough approximations, if its meaning and derivation are clearly understood. It very often leads into error, however, if applied blindly. In the first place, it applies strictly only to problems for which the cost of conductor supports, and other cost not directly proportional to the size of the wire can be neglected. Where such must be included, and bear some other proportion to the wire size, the simple relation of Kelvin's law will not hold true. Similarly when cost of transformers and other equipment and their losses, which may not be inversely proportional to size, are factors, this law does not apply. It is only applicable to the one case for which the costs are in the proportion shown by the equation above, *i.e.*, investment costs directly proportional to wire size and energy-loss costs inversely proportional to wire size. The only safe method for most problems is to revert to Kelvin's original statement, set up an equation of total annual cost, and discover its minimum by the process of differentiation.

As an example of the difficulty which may be gotten into by unintelligent use of Kelvin's law, consider the problem of determination of the *most economical load for a given line* Here the cost equation may be written

$$Y = K_1 + K_4 + K_5 I^2, \tag{141}$$

where I is the current, and K_1 corresponds to K_1 in the previous equation, *i.e.*, costs independent of wire size and of load. K_4 is the investment cost on the wire which in this case is fixed and not proportional to the load. $K_5 I^2$ is the energy-loss cost, being assumed proportional to the square of the load. The solution must be made for the annual cost per unit of load in this case, *i.e.*, Y/I.

$$\frac{Y}{I} = \frac{K_1 + K_4}{I} + K_5 I. \tag{142}$$

$$\frac{d\frac{Y}{I}}{dI} = -\frac{K_1 + K_4}{I^2} + K_5 = 0.$$

$$I = \sqrt{\frac{K_1 + K_4}{K_5}}. \tag{143}$$

This is similar to the solution for most economical wire size except that it includes K_1, the cost which is not proportional to wire size or load (such as the cost of poles and fixtures, perhaps). If the investment cost of the *wire* only is equated to the cost of losses in this case, according to Kelvin's law, the solution will be incorrect.

Similar difficulties are encountered in attempting to apply Kelvin's law to transformer problems, etc. It is more difficult to keep its fundamental relations in mind than to use the basic method as described.

Where there are more than two variables in the problem, these may be held constant for the differentiation operation indicated, the result being an equation with one less variable (Y, or annual cost being eliminated by the differentiation) than the original cost equation. It may be exhibited graphically by either of the methods given in (2) or (3). Figure 375 is an example of such a solution where the variable used for differentiation was *voltage drop*, but the other variables of *wire size* and *load density* were included in the problem. The curves show most *economical voltage drop* for any load density for three standard sizes of wire.

Effect of Variations in Cost.—It is a good plan to indicate, where possible, in the solution of any problem, the effect thereon of variations in the costs used. Not only does this facilitate future study, if costs change, but also it is of assistance in limiting the solution when the costs have not been determined with as

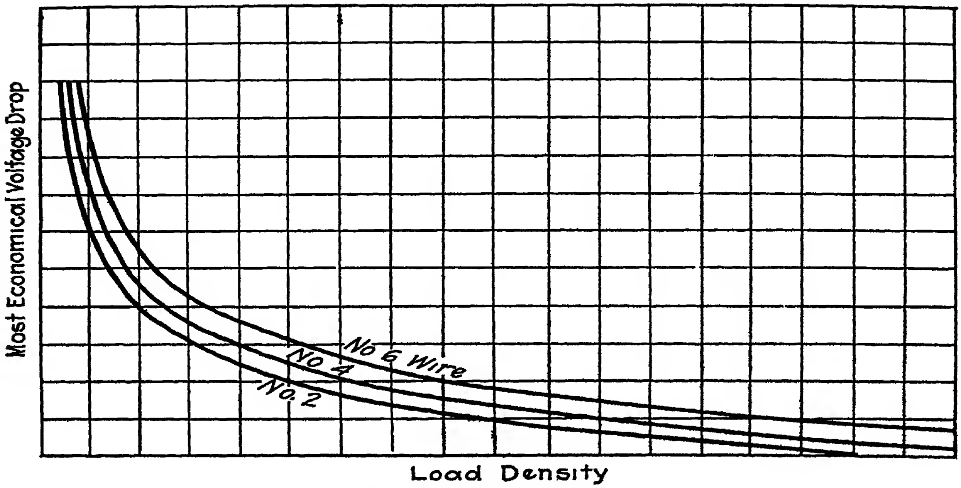


Fig. 375.—Most economical condition—four variables.

great accuracy as would be desired. Energy costs for example are difficult to obtain with a great degree of exactness. If the solution can be so exhibited that the effect of a variation in energy cost of a certain amount, plus or minus, is shown, allowance can be made in the final consideration for the possibility of such an error existing in the cost figures used.

CHAPTER XXXV

PROBLEMS ON PRIMARY LINES

In the following chapters a few of the most ordinary problems encountered on the distribution system, for which an economical solution is desirable, will be described. The general method used will be to indicate the problem, the factors involved in its solution, the form of solution, and the method by which results may be exhibited. As far as possible complicated formulæ and intricate mathematics will be avoided. These are often included in such work in the attempt to work out expressions for as nearly final solutions as possible, but as a rule they only tend to confuse the student and lead to error if each step in the development of equations and constants is not clearly understood. It is not feasible in this work to attempt to give specific, quantitative results, such as the actual wire size which is to be recommended for a given size of load. This might be very desirable if it could be done safely. The affecting conditions are so variable on different systems, however, that sizes which might be most economical in one case would not be so at all in others. Also, it is quite essential, when using any results of such a study, that the methods by which they were reached and the limiting factors involved are thoroughly understood. Otherwise, they may be employed under conditions to which they are not at all applicable. There is grave danger of misunderstanding if actual cost figures and most economical solutions of specific problems are quoted in a work of this kind. For this reason, the methods of attacking the problems herein given are made as general as possible and it should be emphasized that any actual figures given in the computations or the graphs are for illustrative purposes only and are not to be quoted as of general application.

The present chapter will be devoted to the problems which are chiefly concerned with primary lines, *i.e.*, lines from substations to distribution transformers. Naturally there are some cases in which both primary and secondary lines are involved, and also the substation itself must sometimes be included. These are merely somewhat more complicated types of problems to which

similar principles and similar methods apply. Likewise, the instances here given do not by any means cover the whole field but are only more or less illustrative.

The following questions will be discussed:

Determination of the most economical wire size to carry a given load.
Determination of the most economical load for a given line.
Determination of the most economical division of load among several lines.
Determination of the most economical voltage drop over a line.
Determination of the most economical primary voltage.

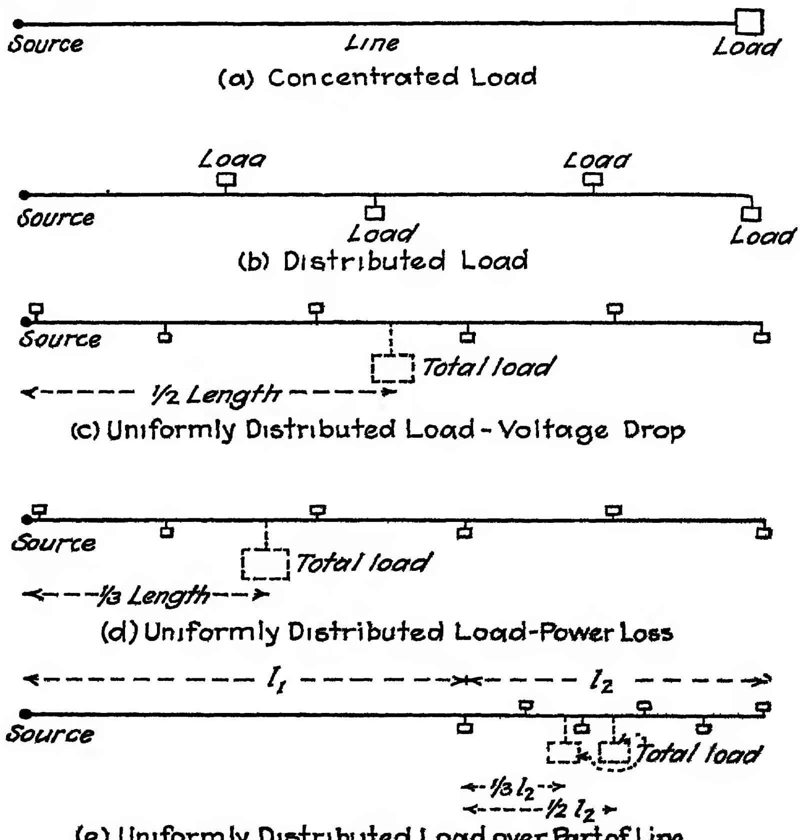


FIG. 376.—Assumptions for distributed and concentrated loads.

Concentrated Loads Assumed.—It will be assumed in most cases, for simplicity, that the loads to be handled can be considered as concentrated, that is, that the line is to be designed for a single load at its end rather than for a distributed load scattered along

its length, Fig. 376 (*a*). This is the case with a power line feeding a single large load or a distribution feeder running from a substation to the feeding point of a distribution circuit. There are many problems, of course, which involve a number of loads which are distributed along the line, Fig. 376 (*b*). In such cases, if desired, the line may be divided into sections between loads and each section considered individually with its proper load (the sum of all loads beyond that section). This method is applicable where the loads are few and comparatively far apart Where the loads are many and small, however, it is likely to be more convenient to consider the load as uniformly distributed over the whole line or over part of it. In case this assumption is made, the principles stated in Chaps. X and XI should be kept in mind, *i.e.*,

(*a*) For uniformly distributed load, the *voltage drop* over the line, to the *end of the line*, is the same as it would be if the *total load* were concentrated at the midpoint.

(*b*) For uniformly distributed loads the *total energy loss* in the line will be the same as it would be if the *total load* were concentrated at *one-third* the distance to the end of the line.

Figure 376 (*c*) illustrates the proper assumption for figuring voltage drop, Fig. 376 (*d*) that for figuring energy loss, and Fig. 376 (*e*), the assumptions to be made when the uniform distribution is over only part of the line.

Economical Wire Size for a Given Load.—It will be assumed that the voltage is established and the route for the line chosen. The problem is to discover what particular size of conductor is the most economical. The choice of sizes will, of course, be limited to sizes which will carry the load with a satisfactory amount of voltage regulation and also sizes which will be mechanically strong enough under the conditions.

The cost equation is as follows:

$$\begin{aligned}\text{Total annual cost} = {} & g_1 \text{ (cost of poles and fixtures)} \\ & + g_2 \text{ (cost of conductor in place)} \\ & + \text{annual cost of operation, inspection, etc.} \\ & + \text{annual cost of energy losses over the line}\end{aligned} \qquad (144)$$

where

g_1, g_2 = percentage annual charges on the property indicated.

Within certain limits, the cost of poles and fixtures can probably be assumed to be practically constant. That is, for wire

sizes from No. 6 up to possibly No. 0, the same poles, insulators, fixtures, etc., would be used with perhaps only a small additional cost for guys as the wire size increases. For large sizes of wire, heavier supporting construction might become necessary, depending on the size of conductor. In the first case, the cost of poles and fixtures might be considered as a constant

(*a*) Cost of poles and fixtures $= K_1L$.

For the second case, part of the cost might be considered proportional to the wire size

(*b*) Cost of poles and fixtures $= K_2 + K_3A$,

where

A = cross-sectional area of conductor in circular mils.
K_2, K_3 = constants determined by construction costs.
L = length of line in feet.

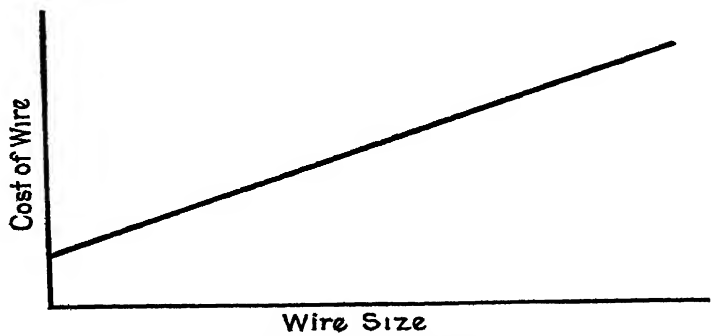


FIG 377.—Cost of wire.

The cost of the conductor itself can usually be divided into two parts, one practically constant for all sizes and one directly proportional to the cross-sectional area. If weatherproof wire is used, the proportion of the total weight represented by the covering will decrease with the size. The price per pound may also vary somewhat with size. If the total cost is plotted against size, as in Fig. 377, a straight line through all points can be approximated, whose equation is of the form,

$$\text{Cost of wire} = (K_4 + K_5A)L,$$

where

K_4, K_5 = constants determined from the curve.

Similarly, the labor cost of erecting the wire can usually also be represented by a constant factor, plus a factor proportional to size.

$$\text{Cost of erecting wire} = (K_6 + K_7A)L.$$

The cost of operation, inspection, etc. will usually be a constant cost, independent of conductor size and can be represented by k_8L.

Energy costs are proportional to the square of the current carried and the resistance of the circuit

$$I = \frac{Kw \times 1{,}000}{E \cos \theta} \text{ for single-phase.}$$

$$I = \frac{Kw \times 1{,}000}{\sqrt{3}E \cos \theta} \text{ for three-phase.}$$

$$R = \frac{\rho L}{A},$$

where

I = line current.
Kw = load in kilowatts.
E = circuit voltage.
$\cos \theta$ = power factor.
ρ = resistivity of conductor material in ohms per mil-foot.
L = length of conductor from source to load.

$$\text{Load at peak load} = I^2R \text{ watts per conductor}$$

$$= \frac{I^2\rho L}{A \times 1{,}000} \text{ kilowatts per conductor.}$$

$$= \frac{k_9L}{A} \text{ where load, conductor material, and length of line are fixed}$$

$$k_9 = \frac{I^2\rho.}{1{,}000}.$$

The cost of energy losses may then be expressed as:

$$\text{Annual cost of energy loss} = \frac{k_9L}{A}(C_1 + 365tC_2), \qquad (145)$$

or

$$= \frac{k_9L}{A}365tC_3, \qquad (146)$$

where

C_1 = demand charge for losses per kilowatt.
C_2 = output charge for losses per kilowatt-hour.
C_2 = combined demand and output charge for losses per kilowatt-hour for this particular type of load (see Chap. XXXIII).
t = equivalent hours (see Chap. XXXIII).

The cost equation may therefore be written as follows:

$$\text{Total annual cost} = g_1(K_2 + K_3A)L + g_2(K_4 + K_5A + K_6 + K_7A)L + k_8L + \frac{k_9L}{A}365tC_3. \quad (147)$$

It is evident that this may be reduced to the form,

$$\text{Total annual cost} = Y = \left(k_{10} + k_{11}A + \frac{k_{12}}{A}\right)L, \quad (148)$$

where

$$k_{10} = g_1K_2 + g_2(K_4 + K_6) + k_8,$$
$$k_{11} = g_1K_3 + g_2(K_5 + K_7),$$
$$k_{12} = 365tC_3k_9.$$

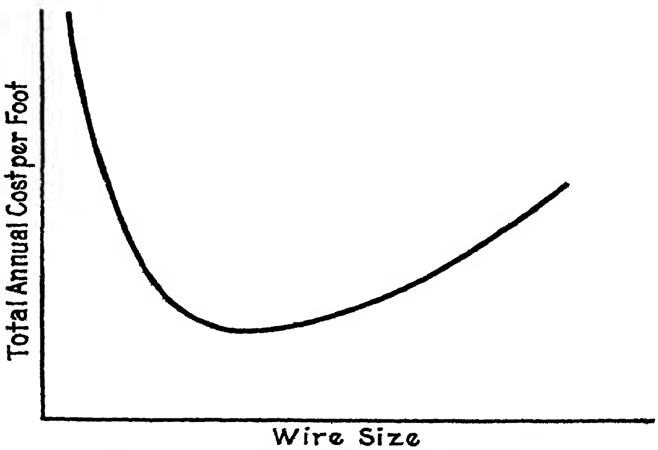


FIG. 378.—Annual cost for any wire size.

This equation may be plotted as indicated in Fig. 378 after the various constants have been evaluated. It should be noted that the length of line enters only as a constant factor, not affecting the minimum size. The size for which the cost is a minimum may be determined by differentiation

$$\frac{dY}{dA} = L\left(k_{11} - \frac{k_{12}}{A^2}\right) = 0.$$

$$A = \sqrt{\frac{k_{12}}{k_{11}}}. \quad (149)$$

This solution is similar to that from which Kelvin's law was derived as indicated in Chap. XXXIV, but it should be noted that k_{11} may include some factors besides annual charges on the conductor itself, such as part of the cost of poles and fixtures.

A number of variations of the above solution are possible. For example, where the study is more general, including the possibility of loads being of different characteristics as to size, power factor, load factor, or hours of use, the elements Kw (load), $\cos\theta$ (power factor), t (equivalent hours), and C_3 (unit cost of energy loss), may become variables. In this case, the method 3 indicated in Chap. XXXIV may be used. A cost equation is written for each standard wire size, and these solved in pairs, giving equations in $Kw/\cos\theta$ as one variable and tC_3 as the

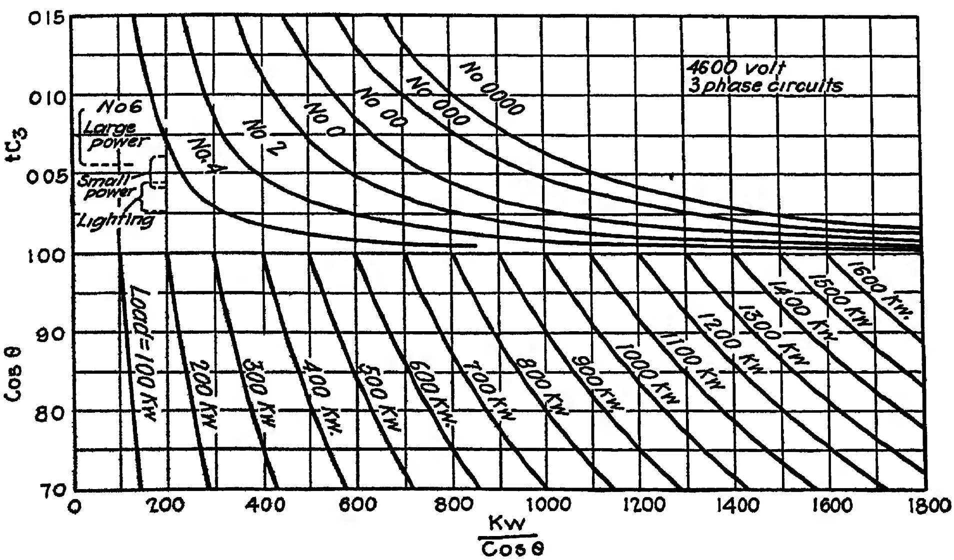


FIG 379.—Economical wire size for three-phase primary.

other. (The latter may be considered as a single variable.) The graph for such a solution is indicated in Fig. 379, the lower curves being a graphical solution of $Kw/\cos\theta$, and the upper ones defining areas for which each size of wire is most economical. The values of tC_3 were obtained in ranges for large power, small power, and lighting. Such a chart is useful for rapid determination of wire sizes in the field.

Economical Load for a Given Line.—In this case it is assumed that the line is built and it is desired to investigate what is the most economical load which it can carry. The general cost equation is the same as in the problem above, *i.e.*,

$$\begin{aligned}\text{Total annual cost} = {} & g_1 \text{ (cost of poles and fixtures)} \\ & + g_2 \text{ (cost of conductor in place)} \\ & + \text{annual cost of operation, inspection, etc.} \\ & + \text{annual cost of energy losses over the line.}\end{aligned} \tag{150}$$

In this problem, however, the variable quantity in the second member of the equation is the current, I, which is, of course, proportional to the load carried when the voltage and power factor are fixed

$$I = \frac{Kw \times 1{,}000}{\sqrt{3}E \cos\theta} \text{ for three-phase, etc.}$$

The first term, cost of poles and fixtures, is a constant ($g_1K_1 = k_1$), the line being already built. Similarly, the second term, cost of conductors in place, is a constant ($g_2K_2 = k_2$). The third term may also usually be considered a constant (k_3). This leaves only one variable term, the cost of energy losses, which, of course, is proportional to the square of the current (I^2) and hence also to the square of the load, it being assumed that the characteristic curve of the load is similar for all sizes of load, and the cost of energy losses C_3, therefore remains the same.

$$\begin{aligned}\text{Annual cost of energy losses} &= \frac{I^2R}{1{,}000}365tC_3 \\ &= k_4Kw^2,\end{aligned}$$

where

$$k_4 = \frac{365 \times 1{,}000RtC_3}{3E^2\cos^2\theta}.$$

R being the resistance of one conductor from the source to the load.

The cost equation, therefore, may be written,

$$\begin{aligned}\text{Total annual cost} = Y &= k_1 + k_2 + k_3 + k_4Kw^2 \\ &= k_5 + k_4Kw^2 \\ (k_5 &= k_1 + k_2 + k_3).\end{aligned} \tag{151}$$

This equation may, of course, be plotted (with the constants properly evaluated), the graph being as indicated in Fig. 380. The comparative cost of carrying different loads can be clearly seen. If a solution for *most economical load* is desired, the equation must be written in terms of *cost per kilowatt* since, of course, the minimum value of Y is when $Kw = 0$. The line is considered

an operating unit, however, and the pertinent quantity is cost per kilowatt.

$$\text{Annual cost per kilowatt} = \frac{Y}{Kw} = \frac{k_5}{Kw} + k_4Kw. \qquad (152)$$

Differentiating the latter equation,

$$\frac{d(Y/Kw)}{dKw} = -\frac{k_5}{Kw^2} + k_4 = 0.$$

$$Kw = \sqrt{\frac{k_5}{k_4}} \text{ for a minimum value of } \frac{Y}{Kw}. \qquad (153)$$

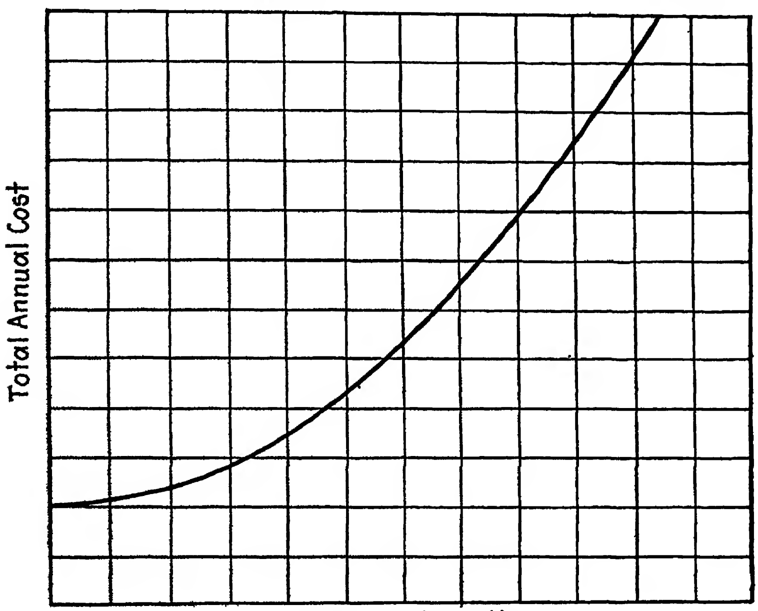


FIG. 380.—Annual cost of line for various loads.

It is to be noted that k_5 in this case includes the cost of poles and fixtures, operation, and other similar constant costs. Herein the solution differs from that for economical wire size where only the costs proportional to wire size were included. Cost of right-of-way, if any, would affect this problem whereas it would not influence the economical wire size. It will also be evident that the most economical load for a line will usually be different from the load for which that line is most economical. This may seem contradictory, but it must be considered that, although a load may be the most economical one for a given line, the annual cost might be still less if the conductor were of larger size.

Economical Division of Load among Several Lines.—It will be assumed that a large load is to be carried by several lines which may be of different lengths and different wire sizes It may be possible to effect a division of load among the several lines and it is desirable to know what division would be most economical.

Referring to the solution for most economical load over a given line, it will be seen that the annual cost for any line may be written

$$Y = k_5 + k_6 R K w^2, \tag{154}$$

where

$$k_6 = \frac{k_4}{R}.$$

The values of the constants are as developed above.

Consider two lines, a and b,

R_a = resistance of conductors in line a.
R_b = resistance of conductor in line b.

Let

Kw_a = the load carried by line a.
Kw_b = the load carried by line b.
k_a = k_5 as applied to line a.
k_b = k_5 as applied to line b.

Total load $= Kw = Kw_a + Kw_b$.

Annual cost on line $a = Y_a = k_a + k_6 R_a K w_a^2$.

Annual cost on line $b = Y_b = k_b + k_6 R_b K w_b^2$.

Total annual cost of both

$$= Y = Y_a + Y_b = k_a + k_b + k_6\,(R_a K w_a^2 + R_b K w_b^2).$$

Substitute for Kw_b its equivalent $(Kw - Kw_a)$,

$$Y = k_a + k_b + k_6[R_a K w_a^2 + R_b(Kw^2 - 2KwKw_a + Kw_a^2)].$$

The annual cost per kilowatt transmitted

$$\frac{Y}{Kw} = \frac{k_a + k_b}{Kw} + k_6\left[R_a\frac{Kw_a^2}{Kw} + R_b\left(Kw - 2Kw_a + \frac{Kw_a^2}{Kw}\right)\right]. \tag{155}$$

The most economical condition is when the total annual cost per kilowatt transmitted is a minimum. Differentiating with respect to the variable Kw_a,

$$\frac{d(Y/Kw)}{dKw_a} = k_6\left(\frac{2R_a}{Kw}Kw_a - 2R_b + \frac{2R_b}{Kw}Kw_a\right) = 0.$$

$$Kw_a = \frac{R_b}{R_a + R_b}Kw. \tag{156}$$

Similarly,

$$Kw_b = \frac{R_a}{R_a + R_b} Kw, \tag{157}$$

and

$$Kw_a R_a = Kw_b R_b \tag{158}$$

It is evident, therefore, that the most economical division of the load on the lines is such that the ratio between the loads is inversely proportional to their resistances. This same solution can be expanded to include more than two lines and the above rule can be made general for any number.

For direct currents, the most economical division of load will take place naturally if the lines are connected in parallel. For alternating currents, however, the inductances have an effect and natural division of current for such lines in parallel is such that the ratio of the current in any circuit to the total load current is the same as the ratio of the admittance of that circuit to the combined equivalent admittances of all the circuits (see Chap. XIV).

For example, for two circuits, one No. 0 and one No. 0000 overhead, with the same length and spacing, the most economical division of a load would be

$33\frac{1}{3}$ per cent to the No. 0 circuit,
$66\frac{2}{3}$ per cent to the No. 0000 circuit.

The natural division would be

44.4 per cent to the No. 0 circuit,
56.6 per cent to the No. 0000 circuit.

(The arithmetical sum of the two currents in the latter case is not 100 per cent since the two are slightly out of phase with each other.)

An interesting example of a comparison of costs between two lines is shown in Fig. 360. The total annual cost of losses is reduced to terms of the ratio between the loads on the two lines (Kw_a/Kw_b) for the particular load in question.

$$\begin{aligned} \text{Annual cost of losses} &= k_6(R_a Kw_a^2 + R_b Kw_b^2) \\ &= k_6 Kw^2 \left[\frac{R_a + R_b m^2}{(1+m)^2} \right], \end{aligned} \tag{159}$$

where

$$m = \frac{Kw_b}{Kw_a}.$$

The actual savings in dollars for the proper division is clearly indicated, especially the appreciably smaller cost of using the most economical division as compared with allowing the larger line to carry the whole load, the smaller being held in reserve ($Kw_b/Kw_a = 0$).

Economical Voltage Drop.—As far as a particular primary circuit is concerned, without regard to other parts of the system, the most economical voltage drop is that occasioned with the most economical size of conductor, or if the conductor size is fixed, it is that caused by the most economical load. It has been shown how these are determined.

Where the amount of voltage regulation between the source and the load is limited, however, other elements may enter the problem. For example, suppose the voltage drop with the most economical size of conductor is more than would be allowable for the requirements of the service. There may be the alternative of using a larger conductor or of installing a regulator at the source (substation) to take care of part of the regulation. The problem in this case becomes one of making a definite comparison of two or more alternatives rather than of determining a specific most economical condition, since regulator sizes are not of infinite variety but come in definite steps, such as for 5 per cent, 7½ per cent, 10 per cent regulation, etc. The solution, then, will consist of determining what size of conductor will give satisfactory regulation with each size of regulator assumed and comparing total annual costs for each of such alternatives considered. The cost equation, neglecting constant quantities such as pole costs, will be of the form,

Annual cost = g_1 (cost of 5 per cent regulator installed)
+ g_2 (cost of space occupied by regulator)
+ annual cost of energy losses in 5 per cent regulator
+ g_o (cost of conductor suitable for use with 5 per cent regulator, installed)
+ annual cost of energy losses on this conductor. (160)

Such an equation will be written for each size of regulator and also for the conductor which would be satisfactory without a regulator. A direct comparison will indicate the economical design. Naturally, it will not be necessary to include any steps (regulator sizes) for which the corresponding conductor will be

smaller than the size which is computed as most economical without regard to regulation.

Another factor which may enter the problem of economical voltage drop when the allowable regulation to the customer is limited, is the consideration of distribution transformer drop and secondary drop. This question involves the study of the economics of secondaries which will be considered in the next chapter. In general, the method of attack would be to determine the annual cost in terms of per cent voltage drop on both primary and secondary system and by comparison to endeavor to arrive at the best relation between the two. In studying voltage drop it will be convenient to refer to the relation,

$$\text{per cent voltage drop} = B \times \text{per cent power loss},$$

where

$$B = \text{a semi-constant, as was explained in Chap. X.}$$

By this means the per cent voltage drop may be introduced into the equation in place of the terms involving power loss.

Still another factor which should be mentioned in connection with voltage drop is the possible loss of revenue if the voltage at the customer is below what it might be practicable to use. For motor loads, this will not be appreciable in most cases, since the power is approximately proportional to voltage times current and if voltage is raised, current consumption is lowered, the kilowatt-hours being about the same. For lighting load, however, a rise in voltage is accompanied by an increase in current, the increase being approximately in proportion to the square root of the voltage. The wattage therefore is approximately proportional to $E^{1.5}$ (see Chap. IV). A 1 per cent increase in voltage at the customer's lamps would therefore result in an increase of approximately 1½ per cent in the load in watts. This is not reflected in the same percentage in the total consumption in kilowatt-hours, however, when the rise in voltage is obtained by a reduction in voltage drop over the distribution lines, since the voltage at light loads (near no load) would be nearly the same regardless of the line drop at maximum load, and drops for intermediate loads would be proportional. Hence a 1½ per cent increase in load at maximum load, *i.e.*, time of maximum voltage drop, would be reduced to ¾ per cent at half load, etc. The net effect, therefore, depends on the shape of the load curve. A convenient way of looking at the situation may be to assume the

energy losses over the line as energy which might be sold if there were no loss and no voltage drop, since per cent power loss and per cent of voltage drop are very nearly equal for lighting load. A 1 per cent power loss means a voltage drop of the order of 1 per cent and a corresponding decrease in wattage at lamps of $1\frac{1}{2}$ per cent. The same relation holds true all through the load curve, so that the per cent power loss could be replaced by $1\frac{1}{2}$ times as great an increase in consumption This increase would earn a return equal to the amount which would be paid for it by the customer, less any incidental expenses occasioned by it as an increase in load. Therefore, it might be assumed, on this theory, that the cost of lost revenue would be properly included, if energy losses were charged at one and one-half times the net return received for energy sold.

This assumption can be qualified by several affecting factors. If the load is distributed over the line, the net *average* effect of reduced voltage drop will be less, being only one-half as much for uniformly distributed load (such as might be the case with the load on a secondary). The increase in load indicated is only true of lamp load and even for that may not always be gained. If the load is considered from the standpoint of illumination, the higher the voltage, the greater the wattage per lamp, but also the greater the illumination and hence perhaps the less number of lamps used. For large loads, especially, it is likely that the amount of illumination would be considered. Heating devices such as electric stoves, toasters, etc. will not be greatly affected, since their consumption is based on the amount of heat required, which will be very nearly proportional to the watts used regardless of the voltage. With primary lines feeding lighting distribution, the voltage at the secondaries near the transformers may be held at about as high a level as is practicable, by use of regulators, and hence, a change in voltage drop in the primary line affects only the use of the regulator and not the customer's voltage. It is well to recognize that a certain loss of revenue is experienced when the service voltage is below the practicable maximum, especially when the voltage is appreciably low, and in certain problems the effect should be included in the cost computations. In most cases, however, the net effect is either small or not present at all and serious error is not incurred by neglecting it.

Economical Primary Voltage.—In choosing the most advantageous primary voltage for a line or a system, there are several

factors which must be considered besides the mere cost of lines and equipment, but which are part of the economic problem The range of possible voltages is not unlimited. A voltage should be used which corresponds to the standard voltages which have been generally accepted (see Chap. VI), unless there is some very good reason for a different choice. Local governmental regulations may limit the voltage. Safety of employees and the public, ability to work the lines hot, reliability of service, etc., are all important considerations which directly or indirectly affect the cost of the system or its operation. The voltages used elsewhere on the system, the present voltage of the line or system, if it is an old one which is to be changed, and the facility for later changes if the load increases to such an extent that they become necessary, have a bearing on the economy and practicability of any voltage to be used. These matters should all be given due consideration in the final decision and, as far as possible, be included in the definite cost comparisons made.

The fact that standard voltages are in steps, *i.e.*, 2,300, 4,600, 6,600 volts, etc., indicates that the problem is one of comparing the cost for any one condition with that for the others, rather than attempting to determine a theoretically most economical voltage. A general cost equation may be written for each voltage step as follows:

Total annual cost = g_1 (those costs pertaining to substation structures and equipment which are proportional to the voltage)
+ annual costs of energy losses in substation equipment which vary with the voltage
+ g_2 (cost of primary lines in place)
+ annual cost of energy losses on primary lines
+ g_3 (cost of distribution transformers in place)
+ annual cost of core losses on distribution transformers
+ annual cost of copper losses on distribution transformers. (161)

The costs of substation structures and equipment must be included in the problem, since there are several items which may be considerably affected by the voltage, such as transformers, circuit breakers, regulators, buses, cables, and other equipment

and, to some extent possibly, the substation structure itself. Likewise, the most economical distance between substations, and hence the number of substations on the system, is a function of the distribution voltage used. It is evident, therefore, that a preliminary determination of loads and load densities to be assumed, and distances between substations for each voltage is essential to a problem when system voltage is being considered. The latter factor, spacing between substations, is, of course, also subject to economic determination and may become part of the problem, but an approximation is helpful as a starting point.

The costs of energy losses in substation equipment are easily determinable for any assumed type of loading. The unit cost of energy losses at the substation will, of course, be somewhat less than on the lines.

The cost of primary lines in place includes a consideration of conductor size. This depends on the voltage since, for a given load, the line current will be inversely proportional to the voltage used. It will probably be necessary to make a study of the most economical size of conductor for each different voltage which is being considered in the problem, giving due weight to the effect on total cost of the comparative costs of wire and regulators. At this point, also, some further determination of the most economical spacing between substations may be made, since the allowable voltage drop, wire size, and regulator size are all factors in that question. Two other elements in the cost of the primary lines, which are affected by the voltage, are the cost of insulators and the amount of pole space required as determined by the necessary clearances. The cost of energy losses on the primary lines will, of course, be determinable for each voltage after the proper wire size and length have been decided.

The cost of distribution transformers will be more or less in proportion to the primary voltage used. In Fig. 52, Chap. VI, was given an indication of the relative costs of distribution transformers at different voltages. The losses on such transformers are obtainable from the manufacturers. Table VI, Chap. IX, shows typical core and copper losses for one line of transformers.

In a study of primary voltage for a system, an increase in load must be anticipated and the design should be such as to be most economical, not only for present load or for load at some time in the future, 5 or 10 years perhaps, but also for the total period. In order to study the economy for changing load it is convenient to set up the cost equation in terms of *load density.*

This factor will enter into most of the factors given in the general cost equation. Losses are proportional to the square of the load on a given line, transformer investment increases with the total load, etc. If the cost equations are reduced to a series of equations for annual cost in terms of load density, these may be plotted and the comparison of economy as the load increases is evident. Figure 381 shows some typical curves plotted as the result of such a study. In most actual cases, where the most economical primary voltage is being studied, the question is one of revising

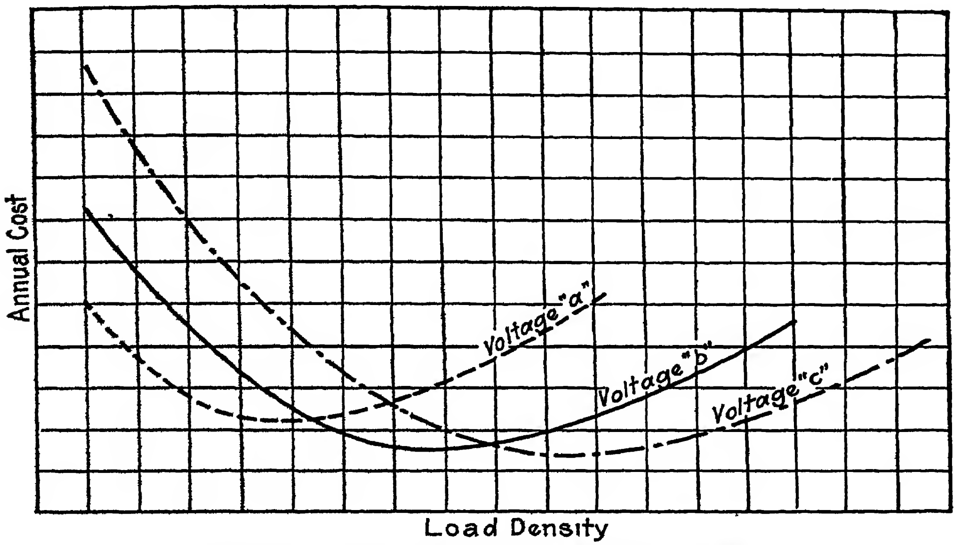


FIG. 381.—Economical study of system voltage.

an old system to one of higher voltage rather than of building a new system. The method indicated above applies equally well to such a problem with the exception that the annual costs on structures and equipment must be taken as the annual costs on the investment necessary to *change old lines and equipment* so that they will be suitable for the proposed new voltage. In figuring annual costs of such work on old materials, consideration must be given to the remaining life of any structure. That life is more or less limited by the age and condition of the old material and governs, to some extent, the annual charge for depreciation on both old and new materials so combined. The costs will also include a consideration for the unused life of any material which must be removed and salvaged, since a certain loss is incurred in so doing.

CHAPTER XXXVI

PROBLEMS ON SECONDARIES

The economical design of secondaries is equally as important a problem as that of the economical design of primary lines. In general distribution, the secondary system probably represents fully as large an investment as the primary and the losses incurred therein are of much the same order. It is therefore evident that a careful study to establish, as far as possible, most economical conditions is well warranted.

The questions to be considered are for the most part those concerning the proper wire size to serve a given load, the proper voltage regulation, the size of transformers to be used, and the best spacing to allow between them (where there is any choice in the matter). Such problems are often somewhat complicated by the fact that both the costs relating to the transformers and those relating to the conductors affect the solution and are more or less interrelated. Where the secondary is continuous and transformers may be spaced practically at any distance desired, the most economical voltage drop, size of conductor, spacing of transformers, and size of transformers are all variables which must be taken into account in all their possible combinations for a complete solution. Of course, there are also simpler problems in which some of these quantities are fixed and, even in the problem indicated above, there are certain limitations which fix some of these to some extent. In the following discussion, for simplicity, the type of secondary whose length is fixed will be first discussed. Then the more intricate question of the continuous secondary will be taken up and the method of solution indicated.

In these problems the load will be considered as uniformly distributed along the secondary. This is a reasonable assumption for the majority of conditions where lighting load or general lighting and small power loads are concerned, although of course it is never strictly true. Concentrated loads of more than the average size are often encountered and these must be given special consideration. For the general case, however, the assump-

tion of uniform distribution is sufficiently accurate. For further discussion of this question see Chap. III. The load for uniformly distributed loading is expressed as load density in kilowatts per 1,000 ft.

Secondary of Fixed Length.—Under certain conditions, the length of secondary fed by any transformer is fixed, either by geographical conditions or by the type of secondary design used, such as that in which each city block is fed by an isolated secondary with the transformer at the middle of the block. The problem is to determine the most economical size of secondary conductor. The degree of loading which is economical for the transformer might also be questioned, *i.e.*, whether it is preferable to have the load on the transformer less than its rated capacity, equal to it, or greater than that rating. This phase of the subject will be taken up first.

Economical Transformer Loading.—The general cost equation for a distribution transformer may be written as follows:

$$\begin{aligned}\text{Total annual cost} = g_1 \text{ (cost of transformer in place)} \\ + \text{ annual cost of core loss} \\ + \text{ annual cost of copper loss.}\end{aligned} \qquad (162)$$

The first two terms are constant for the conditions of this problem, *i.e.*, for a given transformer size the cost of the transformer, of its installation, and also of its core loss are all fixed, regardless of the load. The copper loss will vary with the load:

$$\text{Copper loss} = I^2R,$$

where

I = the load current on the secondary $= \dfrac{Kw \times 1{,}000}{E \cos \theta}$ for single-phase.

Kw = the load in kilowatts.

R = the equivalent resistance of the transformer referred to the secondary side. (See Chap. IX.)

The annual cost of copper loss, therefore, is

$$\text{annual cost of copper loss} = \frac{I^2R}{1{,}000} \times 365tC_3 = k_3Kw^2.$$

$k_3 = \dfrac{365{,}000RtC_3}{E^2 \cos^2 \theta}$ for single-phase transformer.

t = equivalent hours.

C_3 = cost of copper loss per kilowatt-hour.

$$\text{Total annual cost} = Y = k_1 + k_2 + k_3Kw^2 \qquad (163)$$

k_1 = annual charges on cost of transformer and installation.

k_2 = annual cost of core losses.

It should be noted that the unit cost of core loss will be different from that used for copper loss since it is a continuous load.

$$\text{Annual cost of core loss} = \frac{\text{core loss in watts}}{1{,}000} \times 365 \times 24 \times C_4,$$

where

C_4 = unit cost of 100 per cent-load factor energy.

The most economical load is obtained by writing the equation in terms of cost per kilowatt and differentiating.

$$\frac{Y}{kw} = \frac{k_1 + k_2}{Kw} + k_3Kw.$$

$$\frac{d(Y/Kw)}{dKw} = -\frac{k_1 + k_2}{Kw^2} + k_3 = 0.$$

$$Kw = \sqrt{\frac{k_1 + k_2}{k_3}} \text{ for least cost per kilowatt.} \quad (164)$$

It is apparent from the above that the most economical load is that for which the annual cost of copper loss is equal to the annual charges on transformer and installation, plus annual cost of core losses. This may be modified somewhat by the practical consideration that, if the load is larger than a certain reasonable limit, the transformer will be damaged and its life shortened to less than may have been assumed in computing its annual charges. In most cases it will probably be found that the theoretically economical load is considerably in excess of the load which it is practicable to carry on the transformer from the standpoint of safe operation and of allowable regulation.

Economical Conductor Size.—The determination of the most economical size of conductor in this case is very similar to that for most economical primary conductors given in Chap. XXXV. The length of the secondary has been assumed to be fixed, with the transformer located at its midpoint feeding both ways, see Fig. 382. The load is determined by the load density assumed. The problem therefore resolves itself into one of determining the most economical size of conductor for a given load at a given distance. It will be assumed that the poles and fixtures will cost the same for any size of secondary and their cost will be omitted from the solution.

The general cost equation may be written,

$$\text{Total annual cost} = g_1\,(\text{cost of conductors in place}) + \text{annual cost of losses.} \quad (165)$$

If the cost of the conductors in place may be assumed to be represented approximately by a constant amount plus an amount proportional to the size of conductor, the cost may be written,

$$\text{cost of conductors in place} = (K_1 + K_2A)S$$

and

$$\text{annual cost on conductors} = (k_1 + k_2A)S,$$

where

$$S = \text{total length of secondary}$$

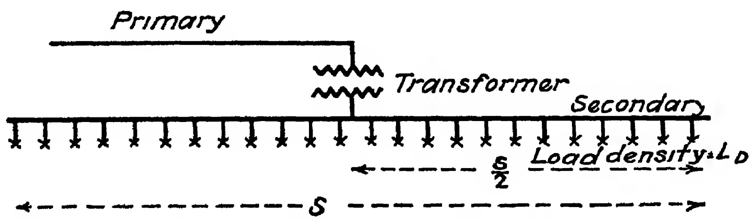


FIG. 382.—Secondary of fixed length.

and K_1 and K_2 are constants determined by plotting cost of wire and its erection against wire size,

$$k_1 = g_1K_1;\; k_2 = g_1K_2.$$

It must be remembered in dealing with single-phase secondaries that the third or neutral wire must be included in the cost of conductors, while it does not appear in the cost of losses if the load is assumed to be balanced normally. It is probably better in this case to include all three wires in the cost of conductors $(K_1 + K_2A)$ and the complete circuit (twice the length one way) in computing losses.

The cost of losses is, of course, proportional to I^2R. If

L_D = the load density in kilowatts per 1,000 ft.
S = the total length of secondary in feet,

$$\text{the total load on the transformer} = L_D\frac{S}{1{,}000}.$$

For this problem, however, the length of secondary is divided into two parts, one each way from the transformer, of length

$S/2$, and load $\frac{L_D S}{2{,}000}$. For uniformly distributed load the loss is equal to what it would be if the load were all concentrated at one-third the distance.

Hence,

$$I = \frac{\frac{L_D S}{2{,}000} \times 1{,}000}{E \cos \theta} = \frac{L_D S}{2E \cos \theta}.$$

$$R = 2\rho \frac{\frac{S}{2} \times \frac{1}{3}}{A}.$$

ρ = resistivity of conductor material.

R = resistance of circuit whose length is twice one-third of the total length $S/2$.

$$I^2R = \frac{L_D{}^2 S^2}{4E^2 \cos^2 \theta} \frac{\rho S}{3A}.$$

$$\text{Annual cost of losses} = 2\frac{I^2R}{1{,}000} \times 365tC_3$$

$$= 2 \times 365 \frac{\rho L_D{}^2 S^3 t C_3}{3 \times 4 \times 1{,}000 A E^2 \cos^2 \theta}.$$

The factor 2 is introduced to include total losses on the secondary both sides of the transformer. If

$$k_5 = \frac{2 \times 365 \rho t C_3}{12 \times 10^3 E^2 \cos^2 \theta}.$$

(k^5 is used to correspond with the similar symbol in the following problem.)

$$\text{Annual cost of losses} = k_5 \frac{L_D{}^2 S^3}{A}. \tag{166}$$

$$\text{Total annual cost} = Y = (k_1 + k_2 A)S + k_5 \frac{L_D{}^2 S^3}{A}. \tag{167}$$

The quantities S and L_D are constant for any given problem, but are introduced in the final equation so that it may more easily be applied to a variety of similar problems.

To determine a minimum value, the above equation may be differentiated.

$$\frac{dY}{dA} = k_2 S - k_5 \frac{L_D{}^2 S^3}{A^2} = 0$$

$$A = \sqrt{\frac{k_5}{k_2}} L_D S. \tag{168}$$

It is an easy matter with the above equations, if the constants are evaluated, to determine the most economical wire size for any given value of load density and length of secondary, and also the comparative annual costs for that size of conductor and any other sizes which might be considered

It will probably be found, as a rule, that the most economical combination of transformer and conductor size is where the most economical wire size is used with the most economical transformer size, which transformer size will usually be a size just large enough to carry the load.

The above study takes no account of allowable voltage regulation. There will usually be a practical minimum limit on wire size imposed by the necessity for keeping voltage regulation within prescribed limits. It was shown in Chap X how the substation regulator may be used to overcome part of the voltage drop on the system but the remainder must be taken into account in designing the secondary lines. The allowable regulation may, for example, be assumed to represent the difference in service voltage between a customer near a lightly loaded transformer at the feeding point of the circuit, see Fig. 110, and a customer at the end of a heavily loaded transformer farthest from the feeding point. The allowable voltage drop must then be divided between the primary line from feeding point to farthest transformer, the transformer, and the secondary. It is conceivable, of course, that the economical portion to be assigned to the transformer might in some cases be less than that produced by its maximum rated load, letting more of the drop occur in the secondary.

A study of economical division of drop may be made by computing the voltage drop per kilowatt load in transformer, secondary, and primary, and comparing that with the annual cost per kilowatt, assuming various possible conditions. It will probably be found in most cases that a satisfactory condition is reached with the transformer loaded to its full-rated load or slightly more (for residence-lighting load), and with the voltage drop on the secondary equal to the difference between the drop in the transformer thus loaded and the maximum regulation which is considered practicable, allowing whatever is necessary for the primary drop. This will possibly be in the neighborhood of 2½ per cent from transformer to farthest customer's service pole. It will also often be the case that the most economical wire size,

found by a theoretical study, such as outlined above, will be too small for the practicable limits imposed on voltage drop.

Another factor which must be considered in choosing a size for the secondary (and also for the transformer in some cases) is that voltage drops caused by starting currents of motors connected to the line should be kept below objectionable values. These dips may in some instances be the governing condition which determines the sizes necessary.

Where increasing load is assumed, the cost over a period of years should be considered. There will often be presented the alternatives of putting in a size of wire which will be sufficient for perhaps 5 or 6 years to come and then changing it to one which will be sufficient for another 5 years, or of putting in the larger size to begin with. The costs may be compared by adding up total annual costs for each size for the first 5-year period, taking due account of the difference in losses and the increasing amount of loss from year to year. The cost of changing sizes at the end of that time will indicate the economy of one size or the other. In the cost of changing sizes must be included not only the labor cost but also the loss in value of the wire taken down, which has not lived out its useful life. Also consideration must be taken of the fact that the old wire is replaced with new wire which has a greater life at the time than the same wire would have had if put up originally.

Transformer Spacing Variable.—Where the type of general design used allows the transformers to be placed along the secondary wherever desired (within the limits of practicability) the determination of most economical conditions involves considerably more study than the problem outlined above (see Fig. 383). There are several variables. The ratio of transformer size to the load carried may be varied. The distance apart or spacing of transformers may vary and the load on each transformer will be determined by the spacing and the load density assumed.

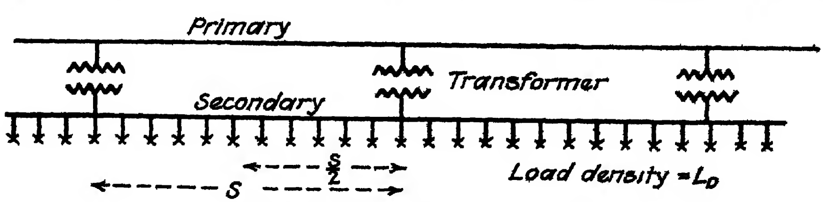


FIG. 383.—Secondary continuous.

Conductor size is a variable and the economical size will depend to some extent on the spacing of transformers. An almost infinite variety of combinations of these variables is possible and a great deal of time may be spent on attempting to arrive at a complete solution of the problem It will usually be found convenient to make assumptions which will simplify the variety of different conditions which must be considered, and proceed to study the problem on that basis. Then, when certain conclusions have been reached, the effect of varying the original assumptions may be taken up.

For example, it may be assumed that the transformers may be made any size, standard or otherwise, which might seem theoretically desirable, that the most economical use of transformers calls for them to be loaded as much as is practicably possible and that they may be spaced at the exact distance desired. After the study has been made on this basis, the effect of using standard sizes of transformers and possible practicable spacings may be introduced.

A statement of the general cost equation and the elements included in its terms may be helpful in clarifying the problem.

Assume the cost of poles and fixtures does not enter the problem.

$$\begin{aligned}\text{Total annual cost} = {} & g_1 \text{ (cost of conductor in place)} \\ & + \text{annual cost of losses on conductor} \\ & + g_2 \text{ (cost of transformers in place)} \\ & + \text{annual cost of core loss in transformers} \\ & + \text{annual cost of copper loss in transformers.} \qquad (169)\end{aligned}$$

Figure 384 indicates the variation of *costs of T.B.W.P. wire* and its erection as plotted for a problem of this kind. It has been assumed in previous problems that the annual costs on the wire followed a straight line. It will be seen that this is not strictly true, but the straight line is not far in error as an approximation. The more accurate costs can be introduced into the problem later if desired. If the straight line is assumed, the cost for conductor for a length of secondary S can be expressed as:

Cost of conductor in place $= (K_1 + K_2A)S$.

Annual cost of conductor in place

$$= g(K_1 + K_2A)S = (k_1 + k_2A)S.$$

(A = cross-sectional area of conductor in circular mils)

For three-wire, single-phase circuits the cost of the neutral must be included. In fact it is more convenient to use the cost of all three wires instead of one since the losses given below are figured on the basis of a complete circuit.

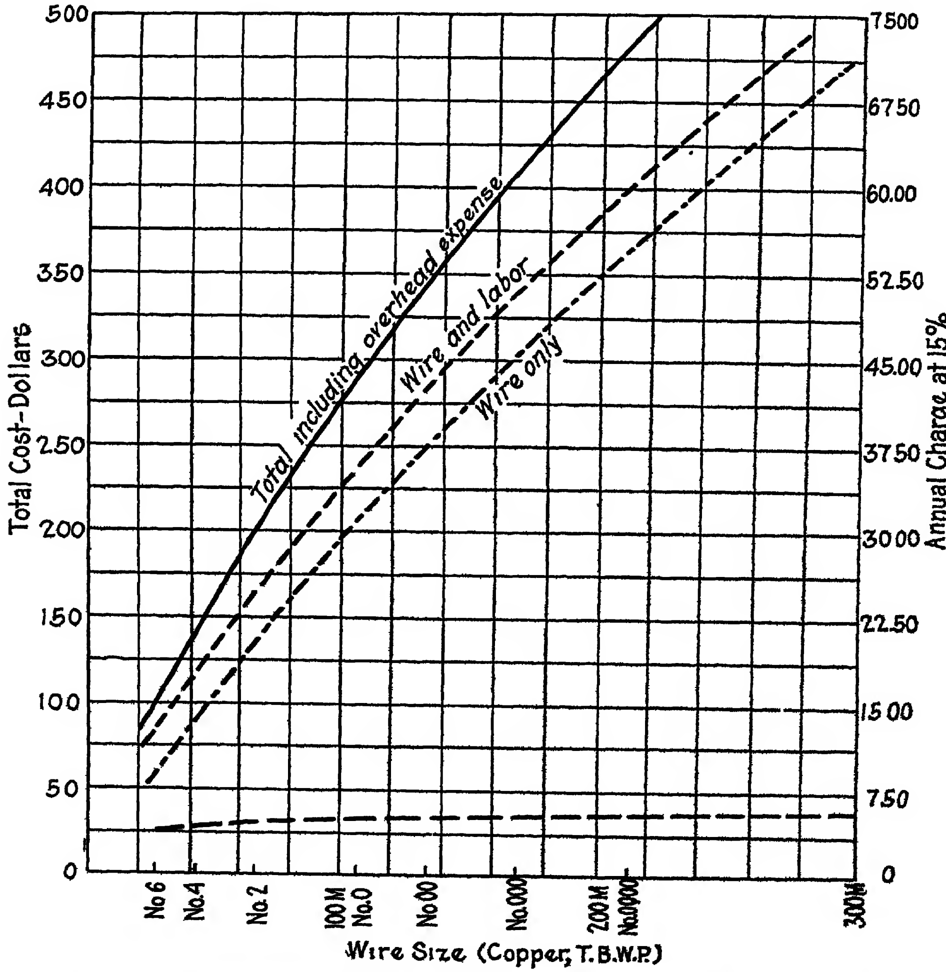


FIG. 384.—Wire costs per 1,000 ft. Three wire secondary; neutral smaller than outsides for sizes above No. 2.

The *cost of losses on the conductor* will depend on the load density. It will be assumed for simplicity that the transformers are of uniform size and uniformly spaced.

Let

S = the spacing between transformers in feet.
I = the total load current on a transformer.
L_D = the load density of the uniformly distributed load in kilowatts per 1,000 ft.
ρ = resistivity of conductor material in ohms per mil-foot.
t = equivalent hours per day for copper loss.
C_3 = cost per kilowatt-hour for copper loss.
C_4 = cost per kilowatt-hour for core loss.
T = transformer size in kv-a.
T' = load on transformer in kilowatts.

The total load on a transformer is

$$\text{Transformer load in kilowatts} = T' = L_D\frac{S}{1{,}000}.$$

$$\text{The transformer current} = I = \frac{1{,}000T'}{E\cos\theta} = \frac{L_DS}{E\cos\theta}.$$

The current flowing each way from a transformer serves the load on a length of secondary of $S/2$ ft , *i.e.*, half way to the next transformer. The line current therefore is $I/2$.

$$I' = \frac{I}{2} = \frac{L_DS}{2E\cos\theta}.$$

The power loss due to this current is

$$I'^2R = I'^2\frac{2\rho\frac{S}{6}}{A}$$

$$= \left(\frac{L_DS}{2E\cos\theta}\right)^2\frac{\rho S}{3A}$$

$$= \frac{\rho}{12E^2\cos^2\theta}\,\frac{L_D{}^2S^3}{A}\text{ watts.}$$

The equivalent length for computing power loss for uniformly distributed load is one-third the total length, which length in this case is $S/2$.

For single-phase load the total loss is figured over twice the equivalent length or $2 \times 1/3 \times S/2 = S/3$.

The above loss is that occurring one way from the transformer. For the total loss for the secondary fed by one transformer, that is, the loss over a length S, thus must be multiplied by 2.

$$\text{Total line loss } \textit{for length } S = \frac{2\rho}{12E^2 \cos^2 \theta} \frac{L_D{}^2 S^3}{A}$$

$$= \frac{\rho}{6E^2 \cos^2 \theta} \frac{L_D{}^2 S^3}{A} \text{ watts}$$

$$= k_3 \frac{L_D{}^2 S^3}{A} \text{ kilowatts} \tag{170}$$

where

$$k_3 = \frac{\rho}{6{,}000E^2 \cos^2 \theta} \text{ which is constant}$$

for a given voltage, power factor, and conductor material. For example, with copper wire, 230-volt secondaries, and power factor at 95 per cent,

$$k_3 = \frac{10.8}{6{,}000 \times 230^2 \times .95^2} = \frac{3.78}{10^8}.$$

It is often convenient to use the loss in terms of loss per unit length, such as per foot. This may be obtained by dividing the above equation by S, the length of the secondary in feet.

$$\text{Total line loss per foot} = k_3 \frac{L_D{}^2 S^2}{A},$$

or

$$\text{Total line loss per 1,000 ft.} = 1{,}000 k_3 \frac{L_D{}^2 S^2}{A} \text{ kilowatts.} \tag{171}$$

It will be noticed that since $L_D S/1{,}000$ is equal to the total load on the transformer in kilowatts (T') the latter expression may be written,

$$\text{Total line loss per 1,000 ft.} = 1{,}000 k_3 \frac{(1{,}000T')^2}{A}$$

$$= 10^9 k_3 \frac{T'^2}{A}. \tag{172}$$

It is evident, therefore, that the total line loss per 1,000 ft. of secondary is directly proportional to the square of the load on the transformer, and is otherwise independent of the length of secondary and load density except as the transformer load is governed by these factors.

The expression may also be written in terms of transformer current,

$$\text{Total line loss per 1,000 ft.} = 10^3 k_4 \frac{I^2}{A}, \qquad (173)$$

where

$$k_4 = k_3 E^2 \cos^2 \theta = \frac{\rho}{6{,}000} \text{ (see above).}$$

The power loss may also be given in percentage of load carried. This is obtained from the above expression by dividing by T'.

$$\text{Total line loss per 1,000 ft. of secondary} = 10^9 k_3 \frac{T'}{A} \times 100$$

$$= 10^{11} k_3 \frac{T'}{A} \text{ per cent of the transformer load.} \qquad (174)$$

(This is *not in percentage of the load per* 1,000 *ft.* which must be obtained by dividing by L_D rather than T'.)

The annual cost of energy losses may be obtained from the above expression by multiplying the loss in kilowatts by the number of equivalent hours of duration per year and the unit cost per kilowatt-hour.

$$\text{Annual cost of energy losses } \textit{for length } S = k_3 \frac{L_D{}^2 S^3}{A} 365 t C_3$$

$$= k_5 \frac{L_D{}^2 S^3}{A}, \qquad (175)$$

where

$$k_5 = k_3 \times 365 t C_3.$$

For example, if $t = 2.5$ hr. per day and $C_3 = 0.015$ per kilowatt-hour, k_3 being the value computed previously,

$$k_5 = \frac{3.78}{10^8} = 365 \times 2.5 \times 0.015 = \frac{0.0517}{10^5} = 5.17 \times 10^{-7}$$

$$\text{Annual cost of energy losses } \textit{per 1,000 ft.} = 10^9 k_3 \frac{T'^2}{A} 365 t C_3$$

$$= 10^9 k_5 \frac{T'^2}{A} \qquad (176)$$

The *voltage drop on the secondary* from the transformer to the point of lowest voltage (midway between transformers) may be computed from the power loss. It will be remembered that the voltage drop to the end of the line for uniformly distributed load is the same as it would be for a concentrated load at one-half the distance. Hence in figuring voltage drop forom pwer loss by the formula $V = BP$, the power loss must be figured at one-half

the distance instead of one-third as was used above for figuring actual power loss. That is,

$$V = BP'$$

where

$$P' = 1.5P.$$
$$P = \text{actual per cent power loss.}$$

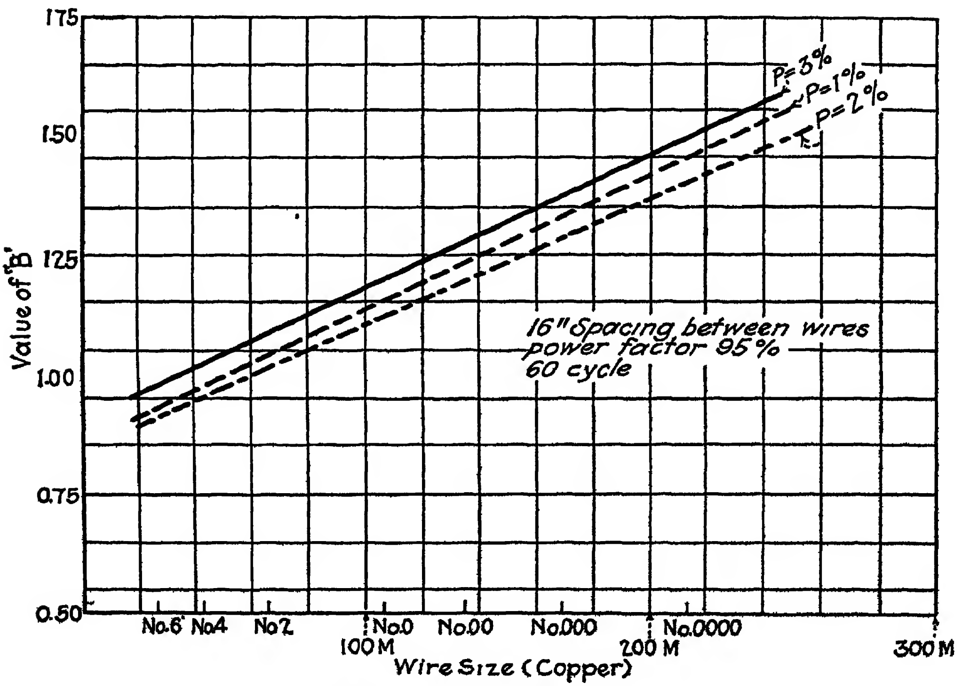


FIG. 385.—Values of B.

The per cent power loss for one-half the secondary ($S/2$) may be written,

$$P = \frac{k_3}{2}\frac{L_D{}^2S^3}{A}\frac{1}{L_DS/2{,}000} \times 100$$
$$= 10^5k_3\frac{L_DS^2}{A}.$$

The per cent voltage drop therefore may be expressed as

$$V = BP' = 1.5 \times 10^5k_3B\frac{L_DS^2}{A}. \tag{177}$$

B is a semi-constant as was explained in Chap. X. For a comparatively small range of values of P or V, however, the value of B can be approximated by a straight line of the equation

$$B = k_6 + k_7 A$$

as is indicated on Fig. 385. The above expression for percentage of voltage drop would then become

$$V = 1.5 \times 10^5 k_3\left(\frac{k_6}{A} + k_7\right)L_D S^2. \tag{178}$$

The *cost of transformers in place* will, of course, vary with the size used. It will be found that if the cost of the transformer is plotted against the size in kv-a., the resulting curve will approximate quite closely a straight line of the form,

$$\text{Cost of transformer in place} = K_s + K_t\,T$$

or

$$\text{Annual charges on transformer in place} = k_s + k_t\,T.$$

The core loss will be practically constant throughout the year and the annual cost of that loss will be,

$$\text{Annual cost of core loss} = \frac{\text{core loss in watts}}{1{,}000} \times 365 \times 24 \times C_4.$$

This also will approximate a straight-line curve when plotted against transformer size.

$$\text{Copper loss} = I^2R_t \text{ watts,}$$

where R_t = the equivalent resistance of the transformer referred to the secondary side.

$$\text{Annual cost of copper losses} = \frac{I^2R_t}{1{,}000}365tC_3.$$

Figure 386 shows the three component costs of a transformer plotted against transformer size, the copper loss being figured for full load. The total cost or the sum of the three approximates very closely a straight line and may be expressed,

$$\text{Total annual changes on transformer} = k_8 + k_9T. \tag{179}$$

The various factors entering into the annual cost of the secondary system have been discussed in some detail as it is believed that if these components are thoroughly understood with the quantities to which they are proportional, their combination in studies of economical conditions can be more easily made. Single-phase secondaries have been assumed but the expressions

given can be similarly developed for three-phase by keeping in mind the differences in methods of figuring power losses, voltage drops, etc.

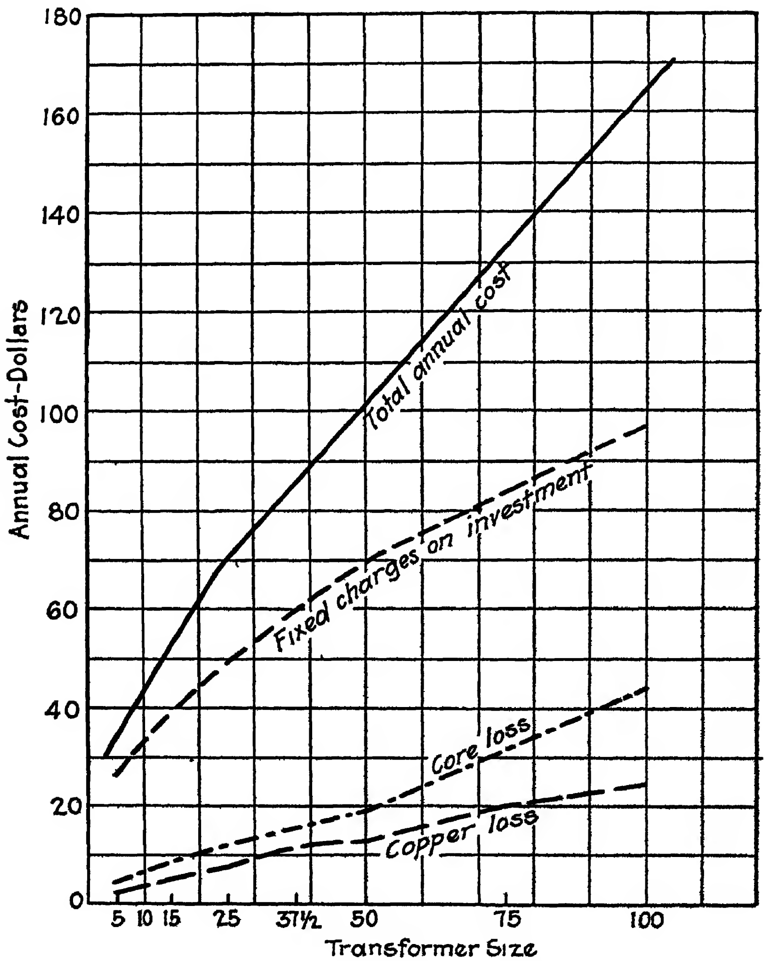


FIG. 386.—Transformer costs—Single-phase transformers.

The general equation of annual cost for a transformer and its secondary of length S can be written in the form,

$$\text{Total annual cost} = Y = (k_1 + k_2A)S + k_5\frac{L_D{}^2S}{A} + k_8 + k_9T. \tag{180}$$

In terms of unit length (1,000 ft) this may be written,

$$Y_{1,000} = \left(k_1 + k_2A + k_5\frac{L_D{}^2S}{A} + \frac{k_8 + k_9T}{S}\right)1{,}000. \quad (181)$$

The general expression for total annual cost of a secondary is subject to further development in various ways in order to determine the details of design. In the form given above there are four variables in the second member which make it hard to study unless further simplification is made. One such method is indicated below.

In equation 181 the quantity T is the size of the transformer in kv-a. The load on the transformer in kilowatts (T') is equal to the load density times the transformer spacing, L_DS If it is assumed that the most economical load on a transformer is the maximum load which it can carry with safety and due regard to voltage regulation, and if a typical percentage of loading for transformers is adopted, such as 80, or 100, or 115 per cent, the cost of the transformer may be expressed in terms of T' by a proper change in the constants.

$$\text{Annual cost of transformer} = k_{10} + k_{11}T'.$$

Since $T' = L_DS$, the annual cost equation becomes

$$Y_{1,000} = \left(k_1 + k_2A + k_5\frac{L_D{}^2S^2}{A} + \frac{k_{10} + k_{11}L_D S}{S}\right)1{,}000. \quad (182)$$

Most Economical Voltage Drop.—Up to this point no limit on the length of the secondary has been imposed except that due to the capacity of the transformer. The cost would be figured for any size of wire, any load density and any transformer spacing (and hence any transformer size). Practically, the voltage drop must be limited to some maximum amount which is consistent with the allowable regulation at the customer. As a rule this will be somewhere between 2 and 3 per cent. It is subject to some economical determination in connection with consideration of economy of primary drops, etc., as was explained before, but for the purposes of this problem it will be assumed to be fixed at say 2½ per cent. The most economical voltage drop may be determined and, if this is greater than the limit set, the limit rather than the most economical drop must govern the transformer spacing.

It has been shown that,

$$\text{The per cent voltage drop} = V = 1.5 \times 10^5k_3B\frac{L_DS^2}{A}.$$

Therefore,

$$S = \sqrt{\frac{VA}{1.5 \times 10^5 k_3 B L_D}}.$$

If this is substituted in the equation for annual cost, the latter becomes,

$$Y_{1,000} = \left(k_1 + k_2 A + k_5 \frac{L_d^2}{A} \frac{VA}{1.5 \times 10^5 k_3 B L_D} \right.$$

$$\left. + \frac{k_{10}}{\sqrt{\frac{VA}{1.5 \times 10^5 k_3 B L_D}}} + k_{11} L_D \right) 1,000$$

$$= \left(k_1 + k_2 A + k_5 \frac{L_D V}{1.5 \times 10^5 k_3 B} \right.$$

$$\left. + k_{10} \frac{\sqrt{1.5 \times 10^5 k_3 B}\sqrt{L_D}}{\sqrt{A}\sqrt{V}} + k_{11} L_d \right) 1,000. \quad (183)$$

The equation involves quite a number of terms but it may be seen that the second member contains only three variables, A, V, and L_D, B being a function of A, and that each of these enters in a simple power or root. The most economical voltage drop may be obtained by differentiating with respect to V, considering the other variables as constants for the purpose.

$$\frac{dY_{1,000}}{dV} = \left(k_5 \frac{L_D}{1.5 \times 10^5 k_3 B} - \frac{1}{2}\sqrt{\frac{1.5 \times 10^5 k_3 B L_D}{A}}\, V^{-3/2}\right) 1,000 = 0$$

Solving for V,

$$V^{3/2} = \frac{1}{2} \frac{(1.5 \times 10^5 k_3 B)^{3/2}}{k_5 (A L_D)^{1/2}},$$

$$V = \frac{1.5 \times 10^5 k_3 B}{\sqrt[3]{4 k_5^2 A L_D}}. \quad (184)$$

With the constants properly evaluated, the most economical voltage drop may be plotted in terms of L_D for each specific size of wire considered ($B = k_6 + k_7 A$). Figure 387 indicates the type of graph obtained. From this it may be determined for what load densities, if any, the length of secondary may be governed by the economical voltage drop. It will probably quite often be found that the economical drop is greater than that practicably allowable and that the length of secondary S will be limited by the maximum drop which is assumed. It is well to make a study of the economical drop, however, as in some

cases it will be found to be less than the practicable limit and a saving will result from its use.

If the value of V to be used is that computed as most economical, the expression for most economical voltage drop may be equated to the general expression for V.

$$V = 1.5 \times 10^5 k_3 B \frac{L_D S^2}{A} = \frac{1.5 \times 10^5 k_3 B}{\sqrt[3]{4k_5^2 A L_D}}.$$

Then the corresponding most economical spacing of transformers is

$$S = \sqrt[3]{\frac{A}{2k_5 L_D^2}}. \tag{185}$$

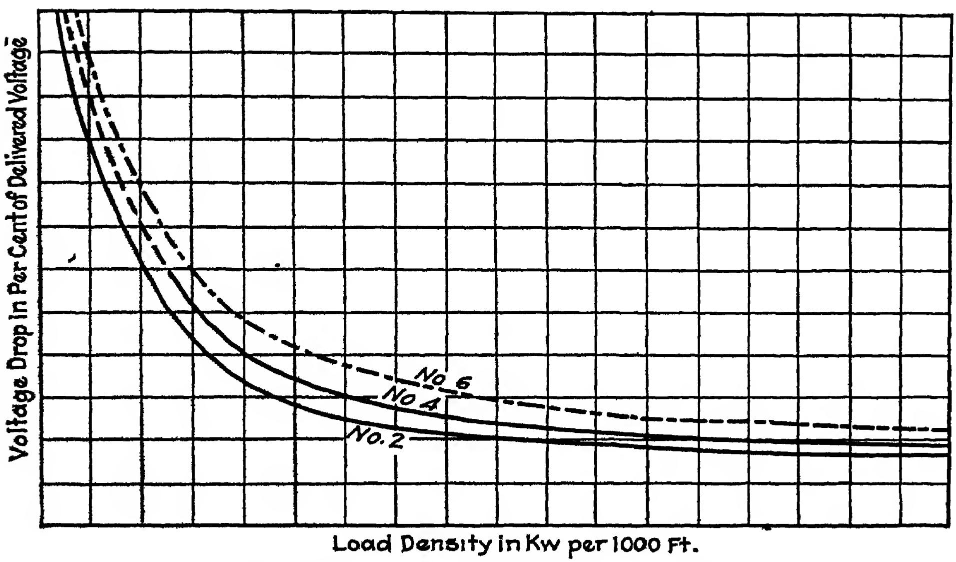


FIG. 387.—Most economical voltage drop

If the value of V is limited to some constant value such as v_1,

$$V = 1.5 \times 10^5 k_3 B \frac{L_D S^2}{A} = v_1.$$

The spacing of transformers for this voltage drop is then,

$$S = \sqrt{\frac{v_1 A}{1.5 \times 10^5 k_3 B L_D}} = k_{12}\sqrt{\frac{A}{BL_D}}, \tag{186}$$

where

$$k_{12} = \sqrt{\frac{v_1}{1.5 \times 10^5 k_3}}.$$

If

$$v_1 = 2\tfrac{1}{2} \text{ per cent for example, and } k_3 = \frac{3.78}{10^8},$$

$$S = \sqrt{\frac{2.5A}{1.5 \times 10^5 \times \frac{3.78}{10^8} BL_D}}$$

$$= 21.0\sqrt{\frac{A}{BL_D}}.$$

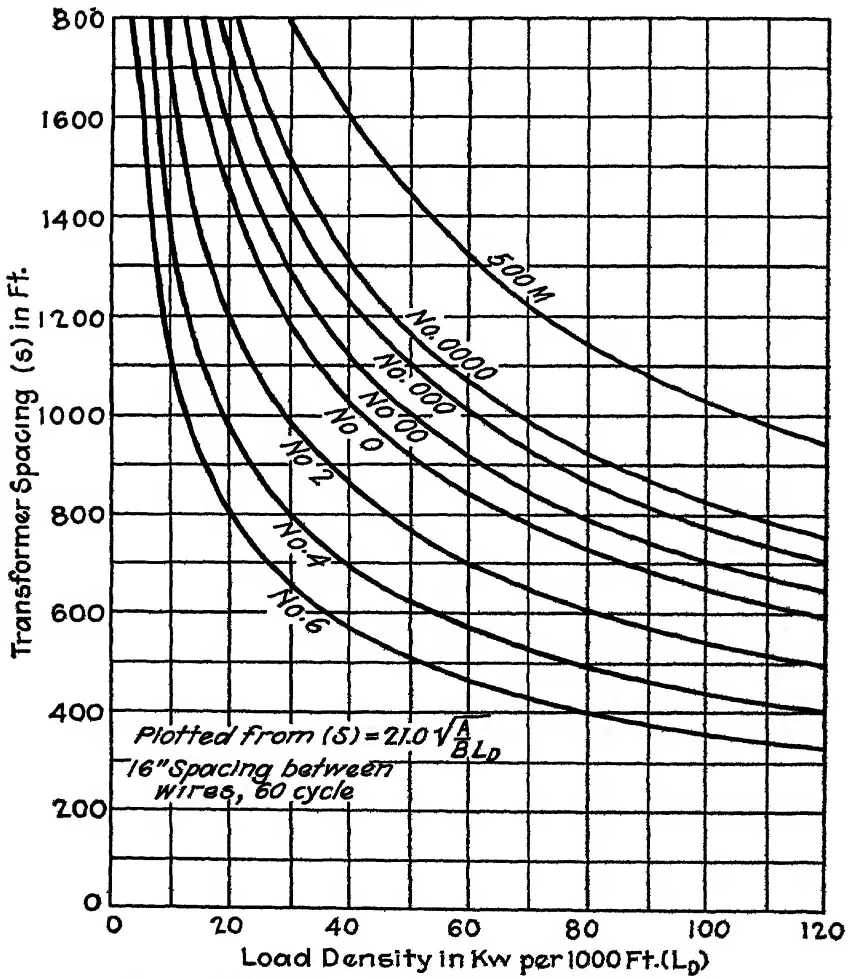


FIG. 388.—Transformer spacing for $2\frac{1}{2}$ per cent voltage drop.

These expressions may be studied by plotting S in terms of L_D for each size of conductor.

Figure 388 shows the graph for transformer spacing governed by 2½ per cent maximum voltage drop.

Most Economical Conductor Size.—The most economical spacing between transformers and the practicable maximum spacing have been developed above in terms of load density and wire size, assuming that the transformer will be just large enough to carry the load. If these values of S are substituted in the general

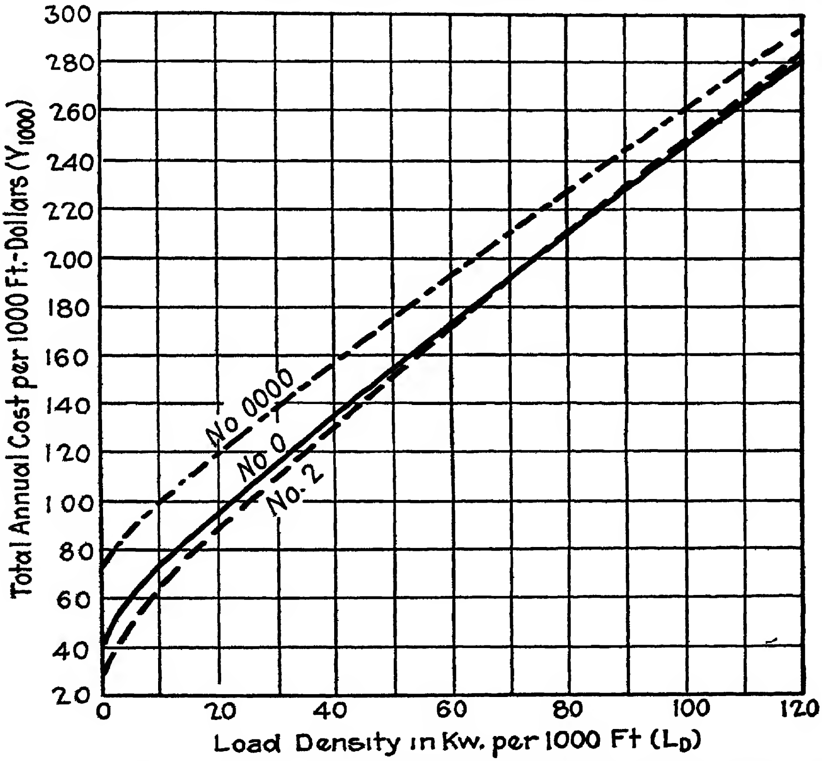


FIG. 389.—Total annual cost of secondary per 1,000 ft. with three different wire sizes—voltage drop limited to 3%. Plotted from Eq. 187 with constants evaluated for a given condition.

equation of cost per 1,000 ft., that equation is reduced to terms of these same two variables. For example, using the expression for limited voltage drop (v_1),

$$Y_{1,000} = \left(k_1 + k_2A + k_5\frac{L_D{}^2}{A}k^2_{12}\frac{A}{BL_d} + \frac{k_{10}}{k_{12}\sqrt{\frac{A}{BL_D}}} + k_{11}L_D\right)1,000$$

$$= \left(k_1 + k_2A + k_5k^2_{12}\frac{L_D}{B} + \frac{k_{10}}{k_{12}}\sqrt{\frac{BL_D}{A}} + k_{11}L_D\right)1,000. \quad (187)$$

If two or three possible sizes of conductor are chosen and the above cost equation written for each one, that cost may be plotted in terms of load density. In this way a graphical comparison may be made of annual costs for different sizes of conductor and the difference in costs for any load density will be indicated as well as the most economical size. Such a graph is indicated in Fig. 389.

If the most economical size is desired more directly, the above equation may be differentiated with respect to A, holding L_D constant.

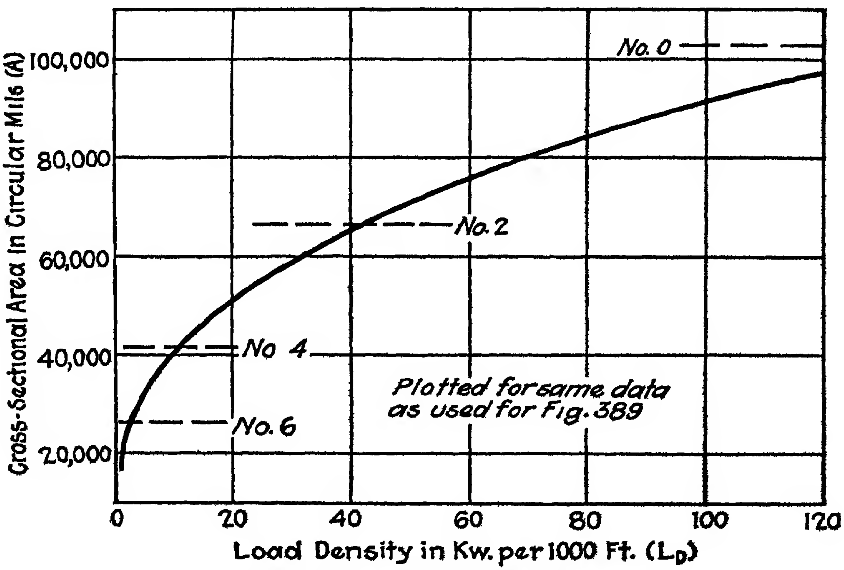


FIG. 390.—Most economical wire size.

Substituting for B its approximate value $(k_6 + k_7A)$,

$$Y_{1,000} = \left(k_1 + k_2A + k_5k^2{}_{12}\frac{L_D}{k_6 + k_7A} + \frac{k_{10}}{k_{12}}\sqrt{\frac{k_6L_D}{A} + k_7L_D} + k_{11}L_E\right)1{,}000$$

$$\frac{dY_{1,000}}{dA} = \left(k_2 - k_5k_7k^2{}_{12}\frac{L_D}{(k_6 + k_7A)^2} - \frac{k_6k_{10}L_D}{2k_{12}A^2\sqrt{\frac{k_6L_D}{A} + k_7L_D}}\right)1{,}000 = 0. \qquad (188)$$

This may be plotted for A in terms of L_D showing the most economical wire size for any load density, the graph being about as indicated in Fig. 390. This curve is harder to determine and probably not so generally useful as the ones for total annual cost as given.

Checking Actual Layouts.—The above method is indicative of how the most economical size of conductor might be determined for any condition. It was assumed in the study that the transformers could be of any desired size and spaced at any desired distance. This cannot be true under actual conditions, however, since transformer sizes are limited to standard stock sizes, 10, 15, 25 kv-a , etc., and their spacing is limited somewhat by standard spans used on the line. The theoretical study will give a basis for the design however, on which the size of conductor can be tentatively chosen and transformer sizes and spacings arranged accordingly as nearly as possible to the theoretical figures. There then may be some uncertainty as to whether the variations introduced by the actual design have been sufficient to change the condition of economy. It is well, therefore, to select several possible variations, two or more wire sizes and several transformer sizes, and compare total annual costs (see general cost equation) for actual field layouts using these variations. In this way a check is made on the theoretical figures and if any divergence from the economical condition has been assumed, it will be discovered. The method of determining unit costs will be the same as indicated under the theoretical discussion.

The same applies to the study of the effect of increasing load. The study of greatest economy was made on the basis of the transformers being loaded to maximum allowable capacity. If the load is increasing, this condition will be reached only at one time, after which they will be replaced. This factor may be allowed for by adjusting the value of T' in the equations. (It may be taken, for example, as 90 per cent of T on the average.) Its influence may also be checked by studying the total annual costs over a period of years for several different possible installations, introducing the effect of increasing losses.

As a rule, the practical procedure will be to select some wire size which will be economical over a range of load densities which will probably be encountered, such as No. 2 copper, perhaps. The transformer spacing is then studied to determine that spacing

at which transformers may be placed for the present lower load densities and which will still be satisfactory for larger densities and larger transformers when the load increases. It will be necessary to replace the transformers only at that time It will usually be found that the possible practicable variations in design are not so numerous as they may at first appear and with a theoretical study as a guide the determination of the practical economical condition is not such an extremely complex problem.

Summary.—The more important formulæ developed and the constants used in the above study of secondary, where the transformer spacing is variable, are given in the following summary:

Annual cost of conductor in place $= k_1 + k_2A$ per foot length

(k_1 and k_2 obtained from ploting curve of actual costs).

Annual cost of conductor in place for length $S = (k_1 + k_2A)S$.

Line loss for length $S = k_3\dfrac{L_D{}^2S^3}{A}$ kilowatts (170)

$$k_3 = \frac{\rho}{6{,}000E^2 \cos^2\theta}.$$

Annual cost of line energy loss for length $S = k_5\dfrac{L_D{}^2S^3}{A}$. (175)

$$k_5 = k_3 365tC_2.$$

Annual charges on transformer (serving length S) $= k_8 + k_9T$ (179)

$= k_{10} + k_{11}T'$

(k_8, k_9, k_{10}, k_{11} obtained from plotting curve of actual costs).

$$T' = L_DS.$$

Total annual cost for length $S = (k_1 + k_2A)S + k_5\dfrac{L_D{}^2S^3}{A} + k_8 + k_9T$. (180)

$$\text{Total annual cost per 1,000 ft.} = \left(k_1 + k_2A + k_5\frac{L_D{}^2S^2}{A} + \frac{k_{10} + k_{11}L_DS}{S}\right)1{,}000. \quad (182)$$

$$\text{Most economical voltage drop} = \frac{1.5 \times 10^5 k_3 B}{\sqrt[3]{4k_5{}^2AL_D}}. \quad (184)$$

$$\text{Most economical spacing of transformers} = \sqrt[3]{\frac{A}{2k_5L_D{}^2}}. \quad (185)$$

$$\text{Spacing of transformers for } v_1 \text{ per cent voltage drop} = k_{12}\sqrt{\frac{A}{BL_D}} \quad (186)$$

$$k_{12} = \sqrt{\frac{v_1}{1.5 \times 10^5 k_3}}.$$

Total annual cost per 1,000 ft. with spacing for v_1 per cent drop

$$= \left(k_1 + k_2A + k_5k_{12}{}^2\frac{L_D}{B} + \frac{k_{10}}{k_{12}}\sqrt{\frac{BL_D}{A}} + k_{11}L_D\right)1{,}000. \quad (187)$$

Symbols.

A = conductor size in circular mils.
L_D = load density in kilowatts per 1,000 ft. of line.
S = spacing between transformers in feet or total length of secondary fed by one transformer.
ρ = resistivity of conductor material in ohms per mil-foot.
E = voltage.
$\cos\theta$ = power factor.
t = equivalent hours per day for losses.
C_3 = cost of copper loss per kilowatt-hour.
C_4 = cost of core loss per kilowatt-hour.
T = transformer size in kv-a.
T' = load on transformer in kilowatts.
v_1 = per cent voltage drop.

Networks.—In the above study, the condition of straight secondaries without branches or loops was assumed for simplicity.

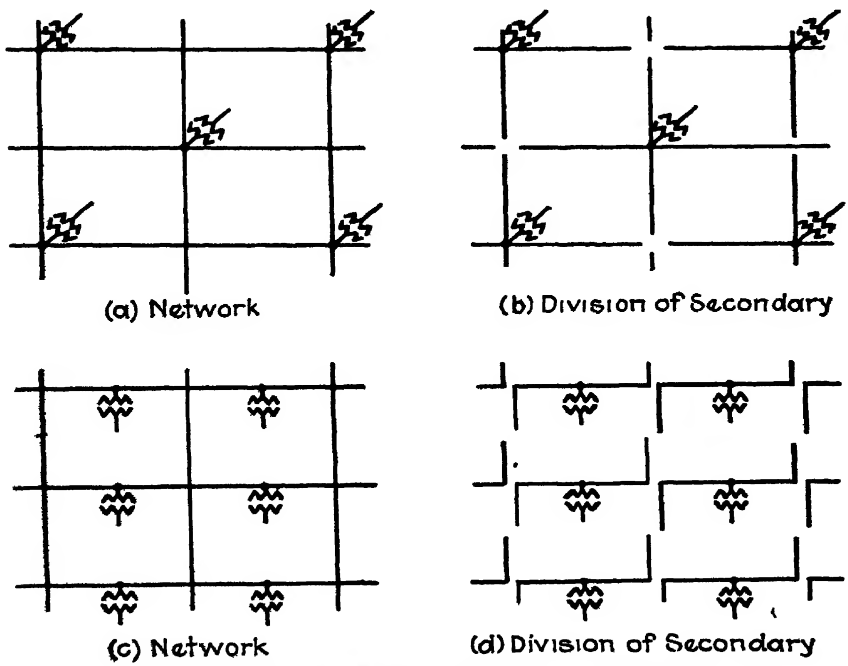


FIG. 391.—Division of current in a network.

It is often necessary to consider such branches and cross-ties, especially where the secondary is part of an overhead or underground network. The methods given in this chapter can be followed, it only being necessary to analyze the conditions

correctly and change the terms of the general cost equation accordingly. A strict determination of voltage and current distribution over a network is a difficult matter, but certain assumptions may be made which will not introduce appreciable error. For example, in Fig. 391, two types of networks are indicated and the assumptions which may be made as to current division among transformers.[1]

In the preceding study the case of overhead single-phase circuits was kept in mind. However, the same general methods may be applied to underground circuits and to three-phase, three-wire, or four-wire circuits, by proper adjustment of terms to fit those cases. With underground circuits an additional consideration is the limit on the amount of current which conductors can carry without overheating. Also in network design it is often necessary to check the cable size for its ability to burn off faults. These qualifying limitations may be considered after the study of the economical condition has been made.

Cost of Low Voltage.—In Chap. XXXV, some consideration was given to the matter of loss of revenue due to the voltage being less than the practicable maximum. It was pointed out that, whereas for lamp load there is a reduction in wattage with voltage, the practicable effect on the consumption and hence the revenue is likely to be negligible, especially where uniformly distributed load is considered. The same points brought out there apply equally well to the voltage drop on secondaries. Of course it must be recognized that unduly low voltage has a serious economic effect in the dissatisfaction it may cause among customers and the resulting retardation of the expansion of the use of electric current.

Cost of Secondary vs. Transformer.—One other small problem having to do with secondaries will be taken up briefly before closing this chapter. It may often occur with customers who are more or less scattered, such as rural customers or three-phase customers in a district where the load is mostly single-phase, that there is a choice of extending the secondary from one transformer to serve another customer or of hanging a separate transformer for that customer. Figure 392 shows three alternatives. The comparison may be made on the basis of annual costs.

[1] A study of the economics of networks is given by W. R. Bullard, in four articles, *Electrical World*, Vol. 91, 1928.

$$\begin{aligned}\text{Total annual cost} = {} & g_1 \text{ (cost of poles and fixtures in place)} \\ & + g_2 \text{ (cost of primary wire in place)} \\ & + g_3 \text{ (cost of secondary wire in place)} \\ & + \text{annual cost of losses on primary wire} \\ & + \text{annual cost of losses on secondary wire} \\ & + g_4 \text{ (cost of transformers in place)} \\ & + \text{annual cost of losses on transformers}\end{aligned} \tag{189}$$

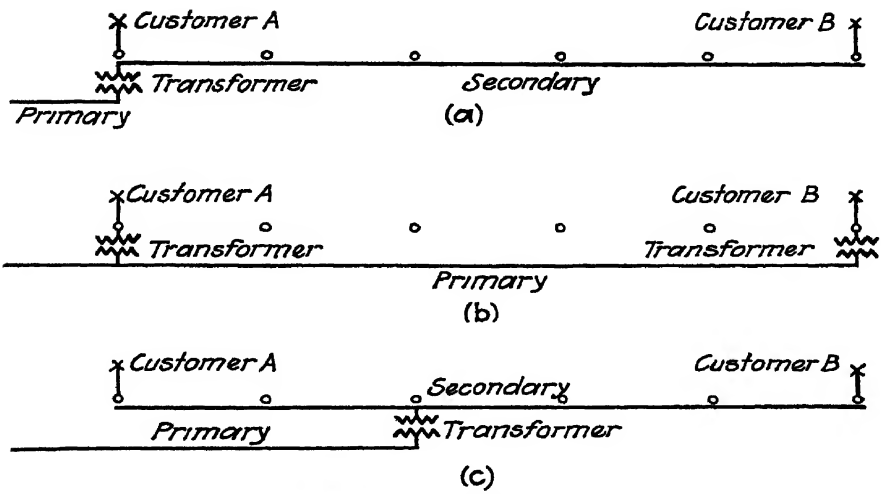


Fig. 392.—Secondary versus transformers.

All of the items do not appear in all alternatives. In one case, the costs include those of secondary and its losses and of one transformer (of perhaps a larger size than would be needed for one customer alone). In the other case, primary and two transformers are involved. In the third, both primary and secondary are included. The cost of poles and fixtures may be the same for both, but in case of long-span farm lines it may be necessary to set extra poles if secondary wires are carried. Sufficient data has been given in previous problems on the method of determining the various items of annual cost so that they need not be repeated here. In one case it was found by such a comparison as the above that farmers could be served economically by secondary where their service poles were within 300 ft. of each other but otherwise separate transformers were preferable (this was on a long-span farm line).

Other Problems.—The problems which have been discussed by no means cover the whole field of problems relating to secondaries but the most important ones have been given The principles brought out may be applied to other conditions if the peculiarities of the particular case are given due consideration.

CHAPTER XXXVII

MISCELLANEOUS PROBLEMS

There are a great many problems of various kinds in connection with the distribution system which present themselves for economic study and which do not fall specifically in any of the classes discussed in the foregoing chapters. Similar principles and similar methods apply, however. Some of these problems will be outlined below and the methods of attack will be suggested. They are but examples of a large number of similar questions which may be encountered.

Economical Span—Rural Lines.—In rural districts, where customers are relatively far apart, the spans of the pole line may be increased beyond what is practicable in urban districts They are limited by certain factors however, such as the strength of the conductor compared with its loaded weight and the relation of the height of poles, clearances required above ground, and spacing between wires, to the sags necessary for the size of conductor used. Copper conductors of the smaller sizes, which are of sufficient conductivity for the load ordinarily carried by a farm line, restrict the spans to relatively short lengths, such as 160 or 175 ft., perhaps. There are other conductor materials which are much stronger however, and which allow longer spans to be used. The economy of the various materials and the spans possible may be studied by determining the costs of lines built with each, the spans being the maximum allowable for the clearances and sags required. A method of attacking the problem is as follows:

1. Select three or four possible conductor materials, such as hard-drawn copper, steel-reinforced aluminum, copper-covered steel, and copper alloy.

2. Select a minimum size of copper which will be satisfactory for conductivity, such as No. 6 perhaps. Determine the equivalent sizes of conductors of the other materials. Select also one or two larger sizes for comparison, since their mechanical strength will be greater and hence spans can be longer.

3. Select one or two standard sizes of poles which will be satisfactory for the purpose, such as 30 and 35 ft.

4. Select a minimum clearance above ground which will meet all Safety Code requirements for the location and will be satisfactory for practical purposes (such as 18 or 20 ft.).

5. Compute the maximum allowable span for each conductor, material and size considered, combined with each pole size assumed. The span will be determined by the strength of the conductor, the loading assumed, and the allowable sag as limited by pole height and ground clearance. (Sag = a in Fig. 393. For example, for 30-ft. poles 5 ft. in the ground, conductor level with the top of the pole, ground clearance 20 ft., a = 5 ft.)

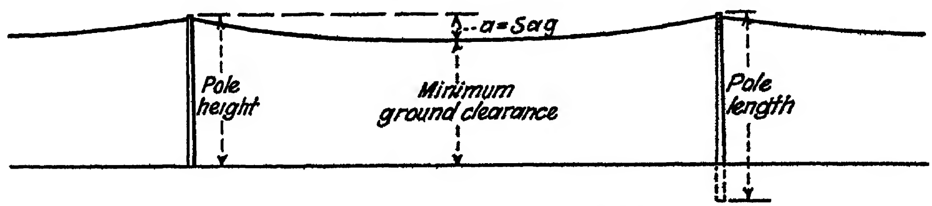


FIG. 393.—Span for farm lines.

6. The cost per mile for each such combination can now be computed, the number of poles per mile being determined by the maximum span. These costs may be tabulated thus:

	30-ft. poles		35-ft. poles	
	Span	Cost per mile	Span	Cost per mile
Material A, copper equivalent:				
No. 6.				
No. 4.				
No. 2.				
Material B, copper equivalent:				
No. 6.				
No. 4				
No. 2				

A direct comparison of cost per mile may be sufficient to determine the most economical design. In some cases, however, it may be advisable to reduce the cost to *annual cost* and include a consideration of cost of losses.

There will probably be some maximum length of span which it will be considered advisable not to exceed in any case, on account of practicable difficulties in laying out the line, etc. If the problem is thus restricted, after the relative economies have been determined as indicated, they may be further studied in relation to the limit thus imposed. Other affecting factors will usually have a bearing on the case but a display of relative costs gives a basis for making a decision.

Power-factor Correction.—A great deal has been written on various occasions about the economy of improving power factor. It is not intended to offer here any further specific evidence as to the benefits to be derived from such correction but rather to indicate the fundamental principles underlying an analysis of costs in that connection. Conditions vary on different systems and a cost analysis for the particular system under consideration should be made as a basis for any study of the advantages of power-factor correction.

The reduction of cost by improving power factor is based on the fact that the line current for any load is inversely proportional to the power factor.

$$I = \frac{\text{kilowatts} \times 1{,}000}{E \cos \theta} \text{ for single-phase.}$$

$$I = \frac{\text{kilowatts} \times 1{,}000}{\sqrt{3}E \cos \theta} \text{ for three-phase.}$$

The reduction made in load current by improving the power factor affects both the demand cost and the output cost for the energy supplied.

The demand costs on distribution and transmission lines and substations are largely dependent on the kilovolt-amperes carried rather than on the kilowatts. The size and hence the cost of transformers, regulators, cables, etc. is determined to a great extent by the currents carried. Some lines are designed for voltage drop but here also an increase in power factor with the resulting decrease in current will effect a decrease in voltage drop and hence in the cost of the line. It may be said, therefore, that the demand cost of the transmission and distribution system is approximately proportional to the kilovolt-amperes and hence to the line current. A reduction in line current accomplishes a proportional decrease in demand cost. At the generating station however, this will usually not be true. The generating station

is designed largely on the basis of kilowatts and a reduction in kilovolt-amperes will not effect a corresponding reduction in the demand cost for it. A careful study of the demand costs from the load back to the generator should be made as indicated in Chap. XXXIII and the effect of increased power factor on each part of the system noted. For example, in a substation which carries diversified load, the change in power factor of any one load will not have a proportional effect on the whole station. If it were a load which entered the station peak only in small part, the remainder of the peak load being of high power factor, such as lighting load, the net effect on demand cost of an increase

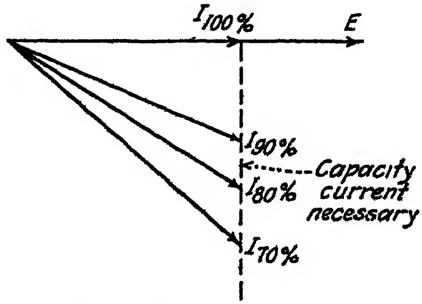


FIG. 394.—Condenser capacity for power-factor improvement.

in the power factor of the load in question might be practically nil. After the demand costs have been analyzed, comparative figures will be available for the load at low power factor and at any power factor from that to unity.

Similarly, output or energy costs are affected by the reduction in line losses due to decreased current. The output at the generating station will not be affected in proportion, however. In fact a decrease in efficiency in the generators may be the result of increasing the power factor beyond a certain point. The effect on the energy cost of increasing the power factor should be studied for each part of the system (generating station, transmission, substation, distribution), keeping in mind that those costs are proportional to I^2. Here also the gain, in the case of substations and transmission lines for which this particular load is only a part of the total, may be much smaller in percentage than for the distribution lines which carry this load only.

Once the effect on costs has been determined by such an analysis as outlined above, the decrease in annual cost of serving

the load for any given increase in power factor may be compared with the annual cost of the corrective measure proposed. Since the amount of kilovolt-amperes of condenser capacity necessary for an improvement of 1 per cent in power factor will increase as the power factor increases (see Fig. 394), and the advantage in decreasing costs is more nearly in direct proportion to the increase in power factor, it is evident that, where any economy can be shown by an increase, there will be some maximum limit beyond which it is not economical to go. That is, for any further improvement in power factor the cost is greater than the benefit.

The means for power factor improvement are, in general (*a*) using motors of high power factor or of leading power factor (synchronous motors, over excited) at the customer's load; (*b*) synchronous condensers at the customer or at the substation; (*c*) static condensers at the customer.

In the study of power-factor improvement by use of condensers which are on during light-load periods as well as heavy, consideration should be given to the possibility of producing at such times loads of such high power factors, or of leading power factors, that they will be undesirable with respect to transmission regulation and generating station operation.

Provision for Anticipated Growth.—When the load is increasing, it is quite necessary when installing or revising a distribution system, to provide capacity for some years to come, as it is obviously uneconomical to be continually replacing lines and equipment. Such provision may easily be carried to extremes however, as it is just as uneconomical to have an excess amount of unused capacity on the system. Just where the line should be drawn is a question which may be treated from the standpoint of economical design. Consider, for example, the distribution transformer. The load may be just too large for a certain size, say a 25-kv-a., and it is questionable whether a 37½ or a 50-kv-a. should be installed. The annual charges on the cost of transformer and installation will be more for the 50 than for the 37½, but the losses for the same load will be less. The problem may be solved by comparing the total annual costs for the one size with those for the other over the period for which the 37½ would satisfactorily serve the load. If the difference between the costs for that period is less than the cost of replacing the 37½ at the end of that time, it will be more economical to install

the 50-kv-a. at once. Otherwise, the 37½ will be the more economical.

$$Y_{50} = \left\{ \begin{array}{l} g_1 \text{ (cost of 50- kv-a. transformer installed)} \\ + \text{ annual cost of copper losses on 50 kv-a. at} \\ \hfill \text{average load for } r \text{ years} \\ + \text{ annual cost of core loss on 50 kv-a.} \end{array} \right\} \times r$$

$$Y_{37} = \left\{ \begin{array}{l} g_1 \text{ (cost of } 37\tfrac{1}{2}\text{-kv-a. transformer installed)} \\ + \text{ annual cost of copper losses on } 37\tfrac{1}{2} \text{ kv-a. at} \\ \hfill \text{average load for } r \text{ years} \\ + \text{ annual cost of core losses on } 37\tfrac{1}{2} \text{ kv-a.} \end{array} \right\} \times r$$

r = number of years the 37½ kv-a. would be sufficiently large.

If K_1 = cost of replacing the 37½ kv-a. with the 50-kv-a. (including all possible items of expense),

The 50-kv-a. installation is more economical if

$$Y_{50} - Y_{37\frac{1}{2}} < K_1.$$

Replacing a Direct-current System with Alternating-current.—The problem of determining exact economical comparison between an old direct-current system and a new alternating-current system is likely to be a very complicated one. Where the direct-current system is adequate for the load, it is doubtful if much advantage can be shown by such a change. There may be some reduction in losses, especially in the substation (losses on the distribution system are not so greatly different), but the cost of these must be compared with the charges on the investment necessary to change over the system, which will be considerable. When the direct-current system is inadequate, however, the cost of increasing its capacity by building new substations, feeders, etc. may be a very large amount. This may be compared with the cost of the alternating-current system, very often to the advantage of the latter, especially if account is taken of the number of years in advance for which each system makes provision and the adaptability to further increase at the end of that time. In counting the cost of the alternating-current system, the cost of changing customers' motors and other equipment must be included (if such changes are to be made by the power company). This may be a considerable amount but it should be remembered that the change is made once for all and its cost can be spread over a long period of years in figuring economy. A discussion

of direct-current versus alternating-current and of distribution networks of both types will be found in Part I of this book

Temporary Lines.—In certain types of problems the alternative is presented of constructing for present needs only or of anticipating future requirements with a somewhat greater present cost. For a simple example, assume a power customer is to be served who can be reached by a mile of line. By a somewhat different route, involving a mile and a half of line, another prospective customer may be reached, whose load is anticipated for some time in the future but the length of that time is uncertain. Assume that the line would cost $1,500 per mile.

Cost of one mile, $1,500	
Cost of 1½ miles, $2,250	
Annual charges on 1 mile at 15 per cent,	$225
Annual charges on 1½ miles at 15 per cent,	$337 50
Difference,	$112 50

Neglecting losses, if it cost $500 to move the mile of line from the first location to the second, that cost would be more than offset by the difference in annual charges if the second customer did not come on for more than 5 years.

Such an analysis may be applied to many cases, such as the use of higher poles in a line than are at present necessary, in anticipation of future requirements, the building of lines on streets instead of in alleys or easements in a district where only a few of the streets are built up and these have houses on both sides, and other similar problems.

In Conclusion.—It is hoped that from the past few chapters the reader may have gained a conception of the importance of economic study applied to the distribution system and the methods of procedure in undertaking such a study. It is realized that very little has been given in the way of simple rules for ready application in the determination of economical conditions, but such rules are likely to be dangerous and to defeat their own purpose unless worked out for the especial conditions under which they are to be used. It is much preferable for the engineer to go into the subject sufficiently to understand the fundamentals and the general methods of solution. For this reason the procedures suggested and the equations developed have been made as general as possible and yet as simple as is consistent with the subject. Complicated mathematics and intricate formulæ have been

avoided as only leading to confusion, and specific cost figures have been used sparingly It has been left to the student to proceed with the data given as a basis and work out his own detailed solutions. He thereby not only obtains valuable rules and graphs which he may apply in his work, but he also develops his judgement in the economical consideration of distribution problems.

In closing, it is wished to emphasize again that economical design is an important part of the design of the distribution system, as an adjunct to the other forms of design treated in this work, *i.e.*, electrical and mechanical design, and any effort spent on it is, as a rule, amply repaid in dollars. While very exact solutions of any problems are usually impracticable due to the variable nature of the quantities involved, the approximations which are possible may be made sufficiently accurate on the average to produce worth-while results in overall economy on the system.

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